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Durability of Buildings - Design, Maintenance, Codes, and Practices

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Preface

This publication is the seventh in a series that began with the First Conference on Building Science and Technology, held in London, Ontario, in March 1982 under the auspices of Canadian Society for Civil Engineering (CSCE). Conferences have been held every two years, except for a 5 year hiatus since the last one in 1992. The conferences continue to provide:

- a forum to present, discuss, and document relevant experience with real issues, for people directly involved in the building industry in Canada, and

- to provide a focus for those individuals concerned with the performance of buildings in general and enclosure-related problems in particular and, in so doing, to attempt to bridge the gap between the various professions within the industry.

In response to feedback from the Sixth Conference and the growing interest in conservation of building stock, the theme chosen for the 1997 Conference is "Durability of Buildings - Design, Maintenance, Codes and Practices". As always, we have tried to obtain a variety of contributions - from papers that are technically detailed, to those that are more general in nature.

This publication provides the details about the material that will be presented over the two days. Only those papers that successfully went through the peer review process and met our time commitment have been included.

To date, each conference has been financially successful. Surplus funds generated from this conference will be donated to the CSCE Building Science Scholarship Fund.

The Organizing Committee

Acknowledgments

Success of this conference is to a large measure attributed to the organizations supporting it. Sponsored by the Canadian Society for Civil Engineering (CSCE), it was co-sponsored by a wide spectrum of organizations involved in Building Science. Their assistance and support are very much appreciated.

Several individuals played a significant role in it and deserve a special mention. Mark Bomberg of the SRC was instrumental in initiating and organizing the Thursday evening program. Michael Lacasse of the IRC-NRCC played a role in advising us on several crucial matters. It was wholly his initiative that resulted in such a strong and active participation by IRC-NRCC.

Contributing authors have devoted considerable time to writing, editing and presenting their research findings. Their interest and devotion has made this Conference and the Proceedings possible. Their enthusiastic participation is appreciated.

The peer review process which ensured a level of technical quality to this conference was the effort of 20 reviewers. These individuals, under the direction of John Straube and Arjan Arenja, volunteered their time and made a valuable contribution towards ensuring the quality and utility of the materials in this publication.

Distribution of the Proceedings at the conference is considered vital for attendees. Accordingly, the text has been reproduced directly from a reduction of the original manuscript submitted by authors. Angela McOrmond and Halina Brezden were instrumental in bringing this to fruition along with their other responsibility of coordinating the conference.

A hiatus of 5 years posed a challenge for the organizers in hosting this conference. Uncertainties about the success of this conference during its conception were, to a large extent, overcome because of the foresight of Dr. Eric Burnett who had retained a start-up fund and notes from the previous conferences.

Despite all the goodwill and a successful history, this conference would not have been rejuvenated without the initiative and foresight of the Organizing Committee made up Arjan Arenja, Vladimir Stritesky, John Straube and John Timusk. These individuals need to be commended for their dedication to the cause of Building Science and their determination to make Building Science a truly technically credible discipline in face of pressures from commercial interests.

Hitesh Doshi
Chairman
7th Conference on Building Science and Technology
Ryerson Polytechnic University

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PERFORMANCE EVALUATION OF EXTERIOR INSULATION AND FINISH SYSTEMS (EIFS)[1]

by
Mark Bomberg[2] Joseph Lstiburek[3] and Fadi Nabhan[4]

Abstract

To control rain ingress, the Exterior Insulation and Finish Systems (EIFS) can be constructed either with a rain drainage control (rain screen) or a face sealed (barrier) approach. While the barrier approach offers economic advantages and may be successfully used under a multitude of climatic and service conditions, water management performance of the wall with EIFS must be carefully evaluated.

More specifically, it is necessary to incorporate several parameters that act on the wall system simultaneously (thermal stress, thermal and moisture originated expansion and contraction, structural movements, material changes caused by weathering and aging, presence of moisture etc.). The interaction among these factors may provide conditions with severity significantly in excess of those achieved when these parameters are tested separately. To this end the authors postulate a new test for evaluation of EIFS integrity under simulated exposure to climatic cycling.

This test involves preconditioning under simultaneous exposure to a water vapor gradient and temperature gradient followed by exposure to severe conditions of one-sided, uni-directional climatic cycling. The testing and characterization of the constituent materials (step 1) coupled with the full-scale test for EIFS integrity under exposure to climatic cycling (step 2) will increase the reliability of the EIFS systems in North America.

Key words: Exterior Insulation and Finish Systems, EIFS, cladding systems, external insulation, base coats, water transmission, moisture engineering, lamina, hygric and thermal stresses, durability, integrity under simulated exposure to climatic cycling test, laboratory testing.

Introduction

Exterior wall assemblies with an exterior insulation finish system (EIFS) contain a substrate (the supporting system) and a cladding system composed of an insulation board, a synthetic coating system consisting of one or more layers of a base coat that embeds a suitably treated reinforcing glass fibre mesh, and a finish coat. The synthetic coating system is commonly

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[1] This paper is an abreviated version of the paper for the J. of Therm. Ins. & Bldg En, Jan 1997

[2] Building Performance, Saskatchewan Research Council, Saskatoon, SK, Canada, S7N 2X8
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called the lamina. Each of these components has a clearly defined function such as mechanical support (strength and rigidity), reduction of heat flow, bonding (adhesion), resistance to crack initiation, resistance to water ingress, and surface texture and appearance.

EIFS cladding exist in two types, Polymer Based (PB) and Polymer Modified (PM) systems. Formerly EIFS were classified as soft coat, thin, flexible for (PB) and hard coat, thick, rigid for (PM). The words, soft, thin, and flexible are attributed to the higher polymer content in the base coat, that results in a flexible thin coating, while the words hard, thick, and rigid are attributed to the relatively high cement content that result in hard, less flexible coating. The cement content does not exclusively separate these two systems. Some PB base coats contain cement, while others are made of completely noncementitious mixes. The components of the two systems are largely identical, except for the thickness of base coat and the method of attachment.

Traditionally, wall systems with EIFS cladding are considered to be barrier walls which means that the exterior face is expected to provide most of the functional requirements of the wall, and in particular acts as the primary (and often the only barrier) to rain ingress. The exterior face, acting as the rain-barrier includes not only the EIFS cladding, but also fenestration, penetrations, and connections between all the components of the building envelope.

The rain-barrier created by the EIFS lamina and its support must remain impermeable to water during its expected service life. The effects of weathering, aging of materials, cracks in the lamina, and the possible deterioration of the wall substrate must be included in the evaluation. Therefore, to evaluate the performance of the wall system, one must evaluate not only its initial performance but also its long-term performance under service conditions.

Issues in moisture management of EIFS cladding

Although there are many examples of satisfactory long-term performance of EIFS, there have been many failures as well, notably failures of the substrate with rain water penetrating through the lamina, joints, and junctions is trapped within the wall system. Sealant joint failure have been reported in 1990[5], in 1991[6],1995[7]; moisture failures have been reported, over the years [7 8 9] (well publicized moisture failures in Wilmington, NC and Vancouver, BC, which led to prohibition of site-manufactured EIFS in Vancouver (1994) and North Carolina (1995).

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[5] Williams, M.F and B. Lamp-Williams, Sealant usage for EIFS, ASTM STP 1069
[6] Mayers J.C. and S.S. Ruggiero, Building Facade Watertightness, ASTM STP 1107, pp11-39
[7] Several papers in ASTM STP 1187
[8] Williams M.F.and B. Lamp-Williams, 1990, ASTM STP 1069, pp 175-194
[9] Several papers in ASTM Special Technical Publication 1187

The central issue of EIFS system evaluation is the management of moisture to ensure system integrity during many years of adverse climatic conditions. During this evaluation, one often faces the dilemma, whether EIFS is to be treated as a component whose suitability must be assessed by the architect / designer or as a cladding system with a proven field performance. Furthermore, there is an additional question of the applicator's skills. For instance, Rosenthal[10] discussing responsibility of the applicator stated:

> "EIFS manufacturers recognize that their systems will only function as intended if they are installed properly. They provide these valuable services because they are genuinely concerned with providing long lasting, quality products.
>
> Despite this involvement in both the pre-construction and construction phases of a project, the EIFS manufacturers are quick to point out, when something goes wrong, that they only sell a product and cannot be held responsible for the design errors of an architect or the misapplication of the subcontractor. But why is that so? If numerous applicators make the same kind of errors , doesn't that implicate the training provided by the EIFS manufacturer? Shouldn't an applicator, in such a situation, be de-certified by the manufacturer? If a particular detail fails repeatedly, shouldn't that be a responsibility of the vendor, rather than the architect or applicator who built the project as specified by the manufacturer? If a manufacturer's representative is on site and fails to detect an error in application, shouldn't the manufacturer be held liable with the applicator?
>
> The overlapping responsibilities, both practical and legal, of the trained applicator, general contractor, manufacturer's representative and architect can be confusing. It can also lead to design or construction errors. Architects and general contractors have to be able to rely on those who know the system best -- the trained applicator and the EIFS manufacturer."
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> "The relative responsibilities of the four parties concerned with installation of the EIFS system -- the manufacturer, the applicator, the general contractor and the architect -- must be spelled out clearly, so that confusion does not lead to faulty application or design errors, so that there is accountability for errors if they occur".

The above quote highlights the significant lack of continuity in the construction process where the continuity of thought and involvement of four parties is necessary to make the EIFS perform. Furthermore, to analyze long-term system performance, one more party may need to be involved, namely the building scientist. Traditional material testing and

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[10] David Rosenthal, abstract of presentation, private communication

performance assessment do not address the long-term performance and durability issues; and learning from construction failures is no longer an acceptable approach in this time and age.

The above quote highlights the importance of proper design and a suitably trained applicator. Of these two, however, the proper design is more important. Proper design means a moisture management system that includes the design of "a second line of defense" under conditions of realistic buildability. Poor installation of a well designed wall system typically works much better than a EIFS product with good inherent properties, installed by a well trained applicator, but following a bad design (specifically a poor design of details).

The authors believe that the moisture management of the whole system will decide whether the subsystems (the EIFS cladding) and substrate will perform satisfactorily. Furthermore, the authors estimate that more than 90% of the EIFS failures could have been avoided by proper design and suitably implemented building site control. If corrective measures are taken by the whole industry and they are early in the construction process, the rate of EIFS failures can be reduced to a small fraction of the current failure rate.

This paper distinguishes between design of cladding and that of a wall system. Cladding is a component of the wall and the functional requirements of cladding do not have to be as extensive as those of the wall. Nevertheless, often exterior cladding is defined as "those components of a building which are exposed to the outdoor environment and are intended to provide protection against wind, water and vapour"[11] or "the non-load bearing clothing of the walls and roof of a building, the skin used to keep the weather out"[12].

The exterior face, and in particular the cladding need not be the only components provided to control moisture entry from the outside if the wall is designed using multiple lines of defense (Bomberg and Brown, 1993). For instance, rain is permitted to pass through the "cladding skin" in drain-screen[13], rain-screen[14] or pressure equalized rain-screen[15] (PER) designs. In the three cases drainage of water is provided by a drainage plane or a drainage plane coupled with an air space behind the cladding. If the air space has sufficient venting to the exterior to equalize the pressure difference between the exterior and the cavity (for instance, over 80% of long-term ("steady state") and 50% of transient wind conditions with frequency 2 Hz or less), the design may be classified as a PER design.

In the barrier wall (face-sealed) approach, however, the exterior face is the only means to control rain entry. The cladding, usually covering most of the exterior face, needs to

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[11] National Building Code of Canada, 1990 edition
[12] Scott, J.S, Dictionary of Building, Penguin Books Ldt., Harmondworth, Middlesex, UK, 1974
[13] Typical drain screen includes drainage plane e.g., building paper without adjacent air space.
[14] Typical rain screen includes drainage plane with adjacent air space
[15] Typical PER includes drainage plane with pressure equilized air space

provide such means. As discussed in later text, a significant test effort is aimed to control rain transfer through the EIFS lamina. Yet, the exterior face of a wall also includes windows and doors and other penetrations. All these penetrations must be equally impermeable to water if the barrier wall approach is to work.

The commentary on Part 5 (dealing with large buildings) of 1990 edition of the National Building Code (NBC) of Canada states:

> "When the sealants of a face-sealed cladding fail, the walls lose their water tightness and airtightness; this translates into severe disability of the envelope in performing its intended functions. As a consequence, face sealed walls require frequent and costly maintenance during the life of building. The approach has little to recommend it and is considered impractical for buildings in Canada."

Brown[16] reviewing Part 9 (dealing with housing and small buildings) of the NBC stated:

> "Part 9 of the Code also generally accepts that cladding alone cannot be expected to provide protection from rain penetration. The intended performance of exterior cladding, as outlined above, to prevent the passage of water and provide drainage if there is a likelihood of penetration is essentially covered within Part 9 by listing acceptable sidings (section 9.27) and requirements for a sheathing membrane (subsection 9.23.17) beneath siding. The requirement for self-furring devices to hold stucco lath 6 mm from the backing (9.28.4.4) is essentially a requirement that stucco be constructed with a drainage layer; in other words, the probability that the cladding will leak is presumed to be not zero".

Thus, in Canada, in contrast to the US, most experienced designers do not rely on sealants as the long-term measure of controlling rain penetration. Other solutions, such as drainable joints, two stage design with sealant on the backer rod and foam, use of expandable gaskets and sealants together are the norm.

Careful examination of laboratory testing reveals that many of these test methods were developed to determine material properties and do not describe the performance of a typical system. Moreover, system performance under certain service and climatic conditions may substantially differ from that defined for a typical "performance" test.

For instance, there are three tests for water transmission and water absorption:

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[16] Private communication

1. A proposed ASTM test procedure uses 100 Pa of water head to observe penetration through 1/3, 2/3 and the entire back surface (150 mm x 150 mm) of the lamina sample. This test is terminated after 72 hours (if complete water penetration does not occur before this time).

2. UEAtc M.O.A.T 22: 1988, Section 3.3.1.1. uses 50 Pa to study water absorption into the lamina materials. The requirement for this test is that the time taken for the entire surface of the base coat to appear damp must not be less than 2 hours .

3. Another proposed ASTM test procedure places the specimen as a divider between the room environment and the test chamber to maintain a constant and specified air pressure across the specimen while spraying water with a dye content to detect water penetration. This test appears very reliable since the exposure conditions are designed to exceed 50 year storm conditions; the specimen size is significant (minimum 1.2 m x 1.2 m) and discharge of the water spray is calibrated for each of four separate sections. A minimum air pressure difference of 299 Pa is also specified.

Among the three tests, the period of exposure to water penetration varies greatly. While a 2 hour criterion is used in the European approach, ASTM calls for a 72 hour test. The other ASTM test appears even more severe, since a high air pressure difference is applied. One may state, for the sake of the reasoning, that each of these tests is likely to prevent an excessive water transmission through the EIFS lamina and therefore any of these tests could fulfill its role as means of characterization for EIFS constituent materials.

Does it mean that an EIFS wall system provided with lamina that passes one of these tests will not suffer moisture damage? Not at all. As stated in the introduction, the exterior face of a wall includes not only the cladding, but also windows, doors, penetrations for HVAC, electrical outlets, and a host of other penetrations as well as the construction/expansion joints. All these penetrations must be equally impermeable to water if EIFS based on the barrier wall (face sealed) approach is to perform. Therefore, evaluation must be focused on the system and not on component testing.

Nevertheless, one has learned a great deal from the testing of moisture performance of the lamina. Research of Piper and Raab (1995) highlighted a few interesting observations:

1. All EIFS specimens (class PB) that failed at 137 Pa pressure had thickness much smaller in the failed area than the average thickness, for instance the base coat was less than 1 mm in the failed area while on average thickness of the base coat was 1.6 mm; 1.8 mm or even 2.6 mm thickness for different samples (total lamina thickness varied from 2.5 mm to 3.6 mm).

2. Except for one case, if the base coat did not fail in the water penetration test when 137 Pa of air pressure was applied, it did not fail when increasing air pressure in steps between 299 Pa and 862 Pa.

3. Water up-take tubes (Rilem test method II.4) were affixed to laminas which failed ASTM test E 331-86 at 137 Pa and to those which did not leak. The Rilem test method showed a much higher rate of absorption through the failed areas, i.e., confirmed the discrepancies obtained in the ASTM test E 331-86 performed at 137 Pa.

The thickness of the base coat has a critical effect but also composition[17], porosity, and aggregate size affect water transmission. The minimum thickness specified by EIMA[18] for the base coat has recently been increased to 1.6 mm (Piper and Raab, 1995) and the new ASTM proposal on testing "Resistance of the lamina to water penetration of class PB EIFS" specifies 299 Pa as the minimum air pressure.

Does this change alleviate the problem? In the opinion of the authors - definitely not. The same ASTM draft proposal states: "In applying the results of tests by this test method, it should be noted that the performance of an EIFS or its components, or both, may be a function of proper installation and adjustment. In service, the performance will also depend on the rigidity of supporting construction and the resistance of the EIFS to deterioration by other causes, such as vibration, thermal expansion and contraction, impacts, etc."

Discussion on the significance of water ingress testing

Two important variables related to water penetration not yet addressed are, the rigidity of the substrate and quality control during application. There are dramatic differences between European and US and Canadian perceptions of EIFS. In Europe the failure rate EIFS is very small (as low as 1%[19]), while field study reported by Kenny and Piper (1995), stated that 91% of examined buildings that were over 9 years old had cracks sufficient to allow water penetration. These diverse surveys may be attributed to two fundamental differences between European and North American practice:

1. *Rigidity and moisture sensitivity of the substrate.* Masonry or concrete substrates that are used in Europe are both rigid and *not sensitive to moisture*. Such substrates can fulfill, to a great extent, the functions of a cladding. Observe that

[17] Michael Rust, private communication:Iceland, with rapid and large changes in temperature, requires highly flexible coatings,
[18] EIFS Industry Members Association
[19] Prof. Hugo Hens during discussion at the ASHRAE conference Thermal VI, Dec. 1995 in Florida after the paper on EIFS failures

the treated gypsum boards are not included in the UEAtc recommended substrate list.

2. *Technical specifications for the base coats are different, namely*:

- Much thicker, min. 2.5 mm thick of dry base coat in Europe against 1.6 mm (now called minimum wet thickness).

- European installation of the base coat is typically made in two layers, while typical North American installation is in one layer (Kenny and Piper, 1995)

- In Europe less Portland cement is used, e.g., maximum cement content is 20% (wt) after the paper on EIFS failures presented of the aggregate. The low cement content reduces water penetration, vapor sorption, loss of flexibility as the cement hydrates and reduces the severity of alkali attack on the glass fiber mesh.

As already recommended by Kenney and Piper (1995) the EIFS installation procedures must be changed to limit the percentage of cement added to the base coat and to require the base coat be a minimum 2.5 mm thick. Note that Kenny and Piper (1995) found in the field study that 64% of the buildings, on which the base coat thickness was determined, had thickness less than the manufacturer's standard. Piper and Raab (1995) showed that water penetration may be associated with uneven thickness of the base coat. While three EIFS samples had an average base coat much in excess of 1.6 mm required by EIMA, in those places where water penetration took place the base coat thickness was 1.1 mm or less.

This discussion highlights the importance of proper design specification that must be enforced by the process of quality control in the application stage. Since maintaining a minimum total thickness and thickness of base coat layer covering the mesh are critical to the hygrothermal performance of EIFS as well as impact resistance, one would also like to impose on the EIFS industry that the base coat thickness be measured and recorded in the log-book of the contractor even if these changes increase the price of EIFS.

It may also be assumed that applying the base coat in two stages makes the process of quality control more effective. The EIFS industry can also examine if there are other means to enforce the appropriate thickness of the base coat layer above the mesh. For instance, one could introduce an innovative type of mesh or coloring admixture that forces the applicator to use enough material to cover the mesh.

It appears that water penetration test directly relates to the quality and thickness of the base coat. To reduce risk of water penetration we need thicker base coats. But substrates used in

North America are often less rigid then those used in Europe. To have a system performing *over the long-term*, there may be a need for higher stain capacity[20] of the lamina used in North America. And there is the question of substrate moisture sensitivity. As noted by French (1992) the most serious and costly type of failure is where water collects in the gypsum causing its paper facing to debond.

A system performance evaluation is more than evaluation of its constituent materials

A substantial number of buildings have developed problems due to water infiltration caused by faulty windows[21], open sealant joints, faulty parapet flashing and improperly flashed louvers (Kenney and Piper, 1995) and other effects introduced by the interface connection between fenestration and EIFS.

Kudder and Lies (1995) underlined the role of discretely applied adhesives in the transfer of water along the surface of the insulation. They indicated that the "risk of widespread system failure" because the moisture penetration is not confined to the vicinity of the moisture entry point. They recommend only full adhesive applications using a notched trowel.

One could estimate the probability of moisture coming through the EIFS lamina and through joints, assess damage potential for this moisture and attempt by means of small-scale tests (such as ASTM test discussed previously) to make sure that no significant moisture damage occurs. Nevertheless, since one has little impact on every industry (trade) involved in the wall construction, one must consider the worst scenario, i.e, that water will find its way into the wall, and deal with it. This would imply incorporating into the design a drainage plane and second line of defense.

A few examples of the second-line-of-defense thinking are given below.

- If the main concern of EIFS moisture performance is the effect of entrapped moisture on moisture sensitive materials such as gypsum board (exterior grade, even when treated with silicones, implies ability to handle contact with water over short periods but not a prolonged exposure to moisture entrapped in the system) then we have several options:

    1. replace gypsum with moisture insensitive cement board,
    2. use a waterproof membrane protection for the gypsum board (that also functions as a drainage plane),

[20] Since modulus of elasticy changes with time, testing must involve "aged" specimens
[21] Brown W.C. et al, "EIFS barrier walls: results from a moisture engineering study", J. Thermal Ins. and Bldg. Envelopes, Jan 1997, pp. 206

3. provide drainage through an air gap between insulation and substrate combined with a drainage plane, or drained air gap created within the thermal insulation, and use partial mechanical attachment (see, Egan, 1995)

- If enhancement of technical solutions appears to be associated with a 10% -30% price increase (price differential between different types of EIFS, Egan, 1995) then the EIFS industry should acknowledge that there is a significant difference in the service free period of different EIFS types. A clear difference between 3 - 8 service free years for the less expensive solution or 15 - 25 service free years (except for color of the surface) for the more expensive solutions should satisfy both the building owners and the EIFS manufacturers.

- If the 30 years service life is to be the norm for the EIFS industry (Fleury, 1995), the North American EIFS industry must address a number of "system" issues. More specifically, there is a general lack of information regarding the following areas:

  1. mechanical properties of the composite of the lamina and thermal insulation, and specifically data on linear or volume changes as a function of moisture content[22]

  2. design and spacing of expansion[23] and control joints (distances may be related to the mechanical properties of the constituent materials)

  3. details of joints[24], particularly those with foam-sealant composites (see: Baerveldt, 1995)

  4. details of mesh attachment on the edge of thermal insulation sheet, details of flashing with flexible membranes rather than with metal (parapet flashing, etc.)

Remarks on testing EIFS constituent materials

Generally, EIFS evaluation can be done with small scale material tests and proven field performance of a specific cladding system design. Based on successful field performance of EIFS applications, one could assess an EIFS performance through prescriptive specifications

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[22] As discussed later in this paper, the hygric stresses are one of the main reasons of crack propagation in the lamina.

[23] Michael Rust, private communication: EIFS systems with EPS are required to place a strip of mechanically attached and bonded to the wall mineral fibre at every floor level above two storeys in height,

[24] Most building scientists do not accept one stage sealant joints, but require two stage joints for instance using a wet selant on the backer rod and low density foam (often one compnent foam), a polyurethane foam / sealant composite. These two options are acceptable when coupled with additional drainage capabilities.

for designs and materials supported only by the testing of constituent materials. However, such assessment would have to be limited to specific designs (including the substrate on which it is installed) and climatic conditions, i.e., to the proven tradition. Observe that the European tradition calls for moisture insensitive substrates (masonry or concrete), proper rain penetration measures such as parging on the back of masonry veneer.

This approach does not require system testing, and since numerous requirements have been developed by American and European testing organizations, there is a sufficient basis for testing of constituent materials. This approach relies on the designers knowledge how to assembly these constituent materials and components into a durable wall system.

EIFS evaluation can also be done with small scale tests to evaluate constituent materials and a full-scale, climatic-cycling test for the whole system. Then, EIFS integrity could be experimentally assessed under the worst case scenario that includes the combination of substrates, insulation, and lamina materials. As the joints and junctions are likely points of moisture entry into the wall system, their inclusion in the system testing becomes a necessity. Furthermore, as climatic caused movements (expansion and contraction) depend on both the size of the uninterrupted lamina and the restraint against movements of the substrate, an appropriately restrained, full scale panel should be used for testing.

This overview started with tests for water transmission through the lamina. To examine use of these tests, however, such diverse systems aspects as the rigidity and moisture sensitivity of the substrate, manner of application of the adhesive, quality control in the base coat installation had to be addressed. Furthermore, such aspects as the degree of moisture sensitivity of materials used in the wall, the probability of moisture ingress through joints and junctions (this probability may be much higher than that of the lamina). In other words, the results of a water penetration test performed on the base coat have a rather small impact in the holistic evaluation that must be undertaken by the designer. To assist the designer, one need a test that evaluates the EIFS integrity under simulated exposure to climatic cycling conditions. This test may be used to confirm experimentally the required level of hygrothermal performance of the whole system.

Concept of the test for EIFS integrity

One of parameters affecting integrity of a cladding system is moisture entrapment. The integrity test should therefore involve conditions that not only may lead to moisture entrapment but also that represent field exposure. Under field conditions the freeze-thaw acts only on one side of the material. Exposing a dry specimen to conditions of one-sided, uni-directional climatic cycling would gradually increase its moisture content until reaching a critical moisture content when a "failure" might occur. However, such a test would

normally require a very long period of exposure. After all, damage caused by moisture usually happens after many years of exposure.

In a cold climate, where a unidirectional heat flow prevails during the winter period, moisture flows towards the cold side, resulting in zones of low moisture content on the warm side and high moisture content on the cold side (whether this zone is located at the cold surface of the specimen or at some distance from the cold surface depends on the nature of the surface layer, periodic and daily oscillation of the outdoor temperature as well as drying ability of the finish coat).

To achieve moisture content that may be near to the critical moisture content for freeze-thaw before initiating the actual integrity test, a 28 days preconditioning procedure will be used. During the preconditioning, EIFS specimens form a divider between two environments:

- 24 ± 2°C with 90 ± 5%RH, representing the room side, and
- -10 ± 2°C, with ambient relative humidity, representing the weather side.

Moisture moves because the thermal gradient creates a strong driving force (a constant thermal gradient has been shown to be one of the most effective methods to achieve moisture saturation in closed-cell cellular plastics). A simultaneous exposure to water vapor concentration and temperature gradients causes accumulation of moisture in the EIFS specimens. How much moisture could be accumulated in the EIFS specimens during the preconditioning period depends on the hygrothermal properties of the constituent materials. If the EIFS lamina, which are placed on the cold side of the assembly do not permit a sufficient flow-through of moisture, there may be more moisture accumulated in the specimen.

Starting the integrity test after moisture content of the EIFS has been significantly increased during the preconditioning period reduces the number of climatic cycles required for the integrity test. In contrast to preconditioning procedure involving constant gradient of temperature, the integrity test employs cycling on the weather side (one-sided cycling). The specimen is placed between two environments and one of them is cycled over 20 days (40 cycles)[25]:

- constant warm side with temperature risen to 30 ± 2°C, and relative humidity 90% RH; and

[25] The required number of cycles is always controversial. ASTM C666 standard for testing concrete requires 300 cycles. ASTM E6.58 subcommittee postulated 60 cycles for testing EIFS. Experience with insulating concrete and other porous materials (cf. ch. 26 of ASTM Moisture Manual) indicate that number of cycles is not as important as reaching the critical moisture content for a part of the system. Therefore a stringent preconditioning procedure was recommended for this test procedure.

- the weather side, chamber temperature varies between -20 ± 2°C (cold period) and 15 ± 3°C (warm period) at ambient relative humidity.

During the integrity test, conditions on the inner surface are kept constant. The air temperature on the outer surface is 30 ± 2°C and water (with a temperature 15 ± 5°C) is sprayed on the surface. This action increases the moisture content of the surface, and if the specimen surface is cracked or if it is prone to hygroscopic / capillary moisture actions, it will likely increase the moisture content within the specimen. Oscillating temperature on one side of the specimen causes moisture movements back and forth within the inner parts of the EIFS specimen. Because of differences in moisture transmission properties of the different layers there would be moisture accumulation at some interfaces. To find if this moisture accumulation, alone or in conjunction with other climatic factors, causes any detrimental effect (delamination, cracking, blistering or sagging) is an objective of this test.

The exposure conditions are similar to the heat-cold cycle specified by UEAtc (June 1988), except that hot and cold periods are somewhat longer, based on experience from the research on the companion test method that is being developed by the ASTM C16 Thermal Insulation committee. However, the severity of the proposed test method is much higher because of the moisture entrapment during the preconditioning stage.

The total cycling period is twelve hours, divided equally into cold and warm exposures. The warm exposure (at least 3 hours at 15 ± 3°C), ends with the transition period not longer than 2 hours. Water at a temperature of 15 ± 5°C is sprayed over the exterior face during the last 60 minutes of the high temperature exposure. Then air in the chamber is cooled to -20 ± 2°C. The cold exposure at -20 ± 2°C (at least 3 hours) ends with a transition period (heating air in the chamber over not more than 1 hour).

Observe that the transition from cold to hot environment is faster than that when the chamber than its cooling. This is in agreement with the concepts of failure envelope for viscoelastic materials and sealants. Gutowski (1990) observed that sealants or adhesives frequently fail due to the initiation and propagation of flaws (cracks) which are developed either at the interface or in the body of the sealant / adhesive, postulating that "the use of fracture mechanics to analyze the mechanism of failure and the expected service life of the bonded structure may thus be useful." Along these lines, Gutowski (1990) showed that the fracture energy for an viscoelastic adhesive is highly dependent on viscoelastic losses which are a function of crack propagation rate, temperature, and the strain level.

The purpose of the integrity test is to assist the designer in evaluating water management of the whole system. Therefore, the test panel should include the same substrate as used in field applications, typical fenestration such as vinyl windows (the highest coefficient of

expansion), decorative frames (if used), wall penetrations, the window flashing and at least one expansion joint.

The level of moisture entrapment achieved during the preconditioning stage depends on the hygrothermal performance of all EIFS layers: the substrate, the thermal insulation, and the lamina. To examine an effect of the finishing coat, it is recommended that a part of the test specimen be provided with the base coat only (i.e, no finishing coat is applied). It is also recommended that a vertical joint between two substrates is located in the centre of the test specimen.

Closing remarks

This paper reviewed some small scale test used for evaluation of moisture performance of the EIFS lamina and highlighted that while they provide good characterization of constituent materials, they do little to assist the designer in predicting moisture performance of the building envelope.

To extend the EIFS applications from traditionally proven wall systems built under known climatic conditions, these small scale tests should be complemented with a full-scale, climatic-cycling test for the whole system. Such a test is proposed in the paper. It was denoted "EIFS integrity test". This test selects the worst case scenario that includes the combination of substrates, insulation, lamina materials and expansion joints, since joints and junctions are likely points of moisture entry into the wall system.

The proposed test involves preconditioning under simultaneous exposure to a water vapor gradient and temperature gradient followed by exposure to severe conditions of one-sided, uni-directional climatic cycling. The testing and characterization of the constituent materials (step 1) coupled with the full-scale test for EIFS integrity under exposure to climatic cycling (step 2) will increase the reliability of the EIFS systems in North America.

Acknowledgments

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Rain Control and Screened Wall Systems

By: J.F. Straube[1] and E.F.P. Burnett[2]

Abstract

Moisture is one of the most important factors affecting building envelope durability and performance, especially in colder climates. The control of driving rain is often a crucial part of a moisture control strategy.

Over the past six years a variety of full-scale wall systems with clay brick veneer, vinyl, and EIFS cladding have been field tested in the BEGHUT test facility. These long-term investigations of the response of wall systems to the south-western Ontario climate have involved observation of both the exterior and interior environments as well as the measurement of the performance of the cladding.

Instrumentation measures sun, wind, rain, and driving rain as well as driving rain deposition from gauges mounted on the walls of the facility. Temperature, vapour pressure, air pressures, and moisture content within the panels have been continuously measured at strategic locations. Standard and non-standard rain penetration testing has been conducted, both on exposed walls and on similar walls maintained in a lab environment.

A summary of some of the more significant preliminary results of this research and its application to wall performance and rain penetration testing, especially for brick veneers, is presented and discussed. The magnitude, incidence, and nature of driving rain deposition is briefly discussed. The results of the comprehensive monitoring of pressure equalization performance of brick veneer walls, and the effect of vent sizes, wind direction, and building geometry are reviewed. Finally, the potential contribution of so-called pressure-equalized rainscreen wall designs to rain penetration control is summarized.

Keywords: brick veneers, rain penetration, driving rain, pressure equalization

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Rain Control and Screened Wall Systems

By: J.F. Straube and E.F.P. Burnett

Introduction

In countries with cold climates, moisture is one of the most important agents leading to building envelope deterioration. Understanding and predicting moisture movement within and through the envelope is therefore of fundamental importance to predicting and improving performance, particularly durability.

Various strategies are used to control moisture in exterior walls. The current Canadian consensus regarding wall design favours multi-layer wall systems employing both a thermally-protected structural component and an exterior screen. For example, the popular masonry veneer "rainscreen" wall system uses an exterior masonry wythe to resist rainwater and a cavity and water barrier to ensure that any water penetrating the masonry screen or accumulating in the cavity is drained outward.

Despite the theoretical advantages of "screened" walls, difficulties realizing the expected levels of both in-service performance and long-term durability remain. As new building products and entire wall systems are brought into use at an increasing pace, there is an urgent need to better predict the performance (including durability) of enclosure systems and the individual sub-systems and materials that comprise them. A better, more quantitative understanding of the wetting and drying mechanisms of common materials and assemblies is also necessary for the identification and quantification of realistic (likely) and extreme (unlikely) conditions which, in turn, can be used to develop better methods of testing and designing against moisture damage.

This paper will consider rain control from a general to a specific level. The following sections will cover: basic moisture control principles that should be employed in the design of above-grade building envelopes; driving rain as a moisture load on walls; a classification system of the various rain control strategies available for walls; and finally, the response of screened walls to rain, especially the water permeance of masonry veneers and the field performance of so-called "pressure equalized rainscreen" masonry walls.

Moisture Control Principles

Moisture Problems

For a moisture-related problem to occur, at least four conditions must be satisfied:

1. a *moisture* source must be available,
2. there must be a *route* or means for this moisture to travel,
3. there must be some *driving force* to cause moisture movement, and
4. the materials and/or assembly must be *susceptible* to moisture damage.

To avoid a moisture problem one could, in theory, choose to eliminate any one of the four conditions listed above. To reduce the probability of having a problem two or more of these prerequisites should be addressed. In reality, it is practically and/or economically impossible to remove all moisture sources, to build walls without imperfection, to remove all forces causing moisture movement, or to only use materials which are never susceptible to moisture damage.

Therefore, *controlling* moisture and reducing the risk of failure by judicious design, assembly and material choices must be the approach taken in the design of durable building envelopes. This not only requires an understanding of moisture and moisture control in wall systems but the cooperation of the owner, builder, several design professionals, regulatory agencies, product manufacturers, etc.

Susceptibility and Vulnerability

Different materials and assemblies are variously susceptible to different kinds of moisture-related damage. Measures and standards are available which attempt to assess the susceptibility of some materials and assemblies to, for example, corrosion, freeze-thaw degradation, staining, and volume change. However, most standard measures of susceptibility are relative not absolute standards.

While the susceptibility of a material to a particular problem (e.g. freeze-thaw deterioration) may be measurable (e.g. standard freeze-thaw tests) it is the responsibility of designers and builders to ensure that a material or assembly is not used in a manner that renders it disproportionately vulnerable — that is, likely to incur a problem. For example, using a material that is supposedly not susceptible to moisture damage (e.g., good quality face brick) in locations with high wetting potential (such as at sills or in garden walls) often leads to durability problems.

The assessment of vulnerability is complicated by the fact that the performance thresholds, and even which physical measures should be used to define thresholds, are unknown or poorly defined for most materials and assemblies. For example, the conditions necessary for mold growth and rot in wood are well known; in contrast, the combinations of environmental and material properties which result in freeze-thaw damage in brick are not as well known.

In general, vulnerability is a function of the local microclimate, which in turn is a function of exposure. Location is the primary determinant of exposure; the location of the relevant portion of the material in the wall, of the wall on the building, of the building on the site, and the geographical location of the site. Vulnerability to moisture damage can also be considered to be a function of the potential for wetting, the potential for storage, and the potential for drying.

Moisture Control

If a balance between wetting and drying is maintained, moisture will not accumulate over time, and moisture-related problems are unlikely. A review of the major sources and stores of moisture and the transport mechanisms typically involved in moisture movement in the envelope is provided below.

Wetting

The three major sources of moisture for the above-grade building envelope are:

- condensation of water vapour transported by diffusion and/or air movement through the wall (from either the interior or exterior),
- precipitation, especially driving rain, both by penetration and capillary absorption,
- built-in and stored moisture.

Driving rain is usually the largest moisture source for above-grade walls. Rain deposition on one or more faces of an exposed low-rise building can easily exceed 100 $kg/m^2/yr$ [1].

Condensation of the water vapour in exfiltrating air during winter conditions can also deposit significant amounts of water within a wall. While diffusion wetting is typically not a powerful wetting mechanism, diffusion is an important means of moisture movement between layers and materials within a wall.

Built-in moisture can be important in some wall assemblies. The use of wet framing lumber, saturated concrete block, or green concrete within a wall may provide a large initial source of moisture.

Wetting by the capillary movement of water from other moisture sources (i.e. rising damp) is generally not a significant problem in Canada (capillarity is, however, a very important as a redistribution mechanism).

Most moisture control strategies have tended to focus on reducing the potential for wetting by, for example, increasing air tightness and interior vapour resistance, reducing the volume of water penetration and absorption, etc. However, it has become generally accepted that most building construction will not be perfect, and thus wetting will occur. Therefore, attention must be given to design approaches that increase a wall's drying and/or storage potential.

Drying

An assembly's drying potential is an important factor in assessing its vulnerability to moisture problems. Moisture is usually removed from a wall by:

- drainage, driven by gravity,
- evaporation from the inside or outside surfaces,

- vapour transport by diffusion, air leakage, or both, either outward or inward; and
- ventilation (ventilation drying).

Drainage is capable of removing the greatest volume of water in the shortest period of time. Hence it is a very important mechanism for moisture control. Provided a clear drainage path exists (e.g. cavities, slopes, drainage openings), a large proportion of rain water penetration or condensation can flow out of a wall. However, a small but significant amount of water will remain attached to surfaces by surface tension and held in materials by capillary forces even in walls with excellent drainage. Cladding or sheathing must be almost saturated by condensation before sufficient volumes of water will bead on the surface for drainage to occur. Therefore it must be assumed that water that cannot be removed by drainage will be stored within a wall.

Under the right conditions moisture not drained from a wall will dry by evaporation or desorption. The resulting water vapour can be transported out of and within the wall system either by diffusion or advection (i.e., combined diffusive and mass flow).

Diffusive drying will generally occur only in an outward direction because very low permeance polyethylene vapour barriers are located on the inside of modern walls in cold climates. Diffusion outward, especially when driven by large vapour gradients in the winter, can remove a significant amount of moisture and be an effective drying mechanism.

Air movement (or leakage) through the envelope can, under the proper conditions, move a large quantity of moisture. While air leakage usually leads to condensation wetting under many winter conditions, it can also remove moisture. Periodic reversals of air flow from exfiltration to infiltration (when the wind changes direction for example) can allow drying even under winter conditions. Similarly, winter-time stack-effect-driven infiltration and summer exfiltration can cause drying.

Ventilation, or air flow through a space behind the cladding, uses the drier outdoor air to transport water vapour out of the wall. A recent study [2] suggests that ventilation drying can be useful, but more research is required to quantify its benefits.

Capillary transport acts to redistribute moisture within a system. For example, water on the back of a brick veneer or wood siding will be drawn to the exterior face where it can evaporate.

Storage

The ability of a wall assembly to store moisture may be an important measure of its durability because storage acts as a vital buffer, or capacitor, between the deposition and removal of moisture. However, if the volume of stored water exceeds the safe level for a material and is present for long enough, deterioration can occur, i.e. rot of wood, freeze-thaw damage of masonry, and corrosion of metal. Therefore, the two most important characteristics of moisture

storage are: how *much* moisture can be stored and for what *duration* without crossing a performance threshold.

Sorption of water vapour by hygroscopic materials is an important storage mechanism. A significant amount of moisture can be stored within a porous material as water vapour molecules adsorb to the large internal surface areas of materials such as wood, concrete and masonry. When a porous material has adsorbed all the moisture it can, further moisture will be stored in the pores and cracks within the material by capillary suction, or by *absorption*. Only when all pores are filled with water is a material saturated. For example, wood will adsorb moisture up to approximately 30% of its mass in the adsorbed state and fully saturated wood can hold two to four times this amount of water. When all easily filled pores of a material are filled with water, the material is capillary saturated. A capillary saturated material will generally not be able to store any more moisture. Water stored in pores generally must leave in vapour form.

Driving Rain

The basic moisture control principles that should be employed in the design of above-grade building envelopes have been outlined above. The remainder of the paper will examine driving rain and wall response to rain deposition in greater detail.

Air leakage condensation, one of the major sources of wetting, has received a great deal of attention in the past. However, the amount of water deposited on the above-grade building envelope by driving rain is generally larger than any other source, including condensation, in almost all cases. Despite the importance of driving rain to building performance, there is a lack of quantitative data relating to the magnitude, duration, frequency, and deposition of rain on buildings.

The deposited rain can result in staining, leakage, dimensional change, freeze-thaw damage, leaching, efflorescence, and biological deterioration. Water penetration of the cladding can cause similar problems in the interior layers of the wall. Vapour diffusion can move water that penetrates or is stored in the cladding inward where it can cause serious wetting of framing, sheathing, etc. [3].

Driving rain, both in the free wind and deposition on a test house, have been measured for more than one year at the Building Engineering Group's (BEG) full-scale natural exposure and test facility, the Beghut. Results from these measurements and the existing literature are reviewed and summarized below.

Rain and Wind

Driving rain can be defined as the amount of rain that passes through a vertical plane in the atmosphere. Lacy [4] proposed a simple equation relating wind speed and rainfall intensity to driving rain :

$$r_v = 0.208 \cdot V \cdot r_h = DRF \cdot V \cdot r_h \qquad (1)$$

where, r_v is the rate of rain passing through a vertical plane ($l/m^2/h$),

V is the average wind velocity (m/s), and

r_h is the average rainfall rate on the ground ($mm/m^2/h$).

The proportionality constant in Equation (1), the ratio of rain on a vertical plane (driving rain) to rain on a horizontal plane (falling rain) is defined here as the driving rain factor (DRF). Recent field studies and theoretical analysis by BEG [1, 5] have found that the value for the DRF ranges between 0.20 to 0.25 for average conditions but varies considerably for different rainfall intensities and rain storm types (from more than 0.5 for drizzle to 0.1 for intense cloudbursts).

When wind encounters a building, stream lines and pressure gradients form around it. While it is clear that driving rain is re-directed by these streams of air, accounting for this effect is difficult. We have introduced a linear factor, the rain admittance factor (RAF), that transforms the rate of driving rain in the free wind (i.e. outside of the region disturbed by a building) to the rate of rain deposition on a building. The RAF accounts for the effect of a building on driving rain in the free wind and is believed to be a function of the building's aerodynamics, the wind's angle of attack, raindrop diameter, and wind speed.

Lacy's simple model of driving rain in the free wind can now be extended to predict driving rain deposition on the vertical face of a building using:

$$r_{bv} = RAF \cdot DRF(r_h) \cdot \cos(\theta) \cdot V(h) \cdot r_h = RAF \cdot \cos(\theta) \cdot r_v \qquad (2)$$

where r_{bv} is the rain deposition rate on a vertical building surface ($l/m^2/h$),

V(h) is the wind speed at the height of interest (m/s),

θ is the angle between the normal to the wall and the wind direction, and

RAF is the rain admittance factor, where $RAF = r_{bv} \div (r_v \cdot \cos(\theta))$

The literature contains few references of simultaneous measurements of driving rain in the environment and driving-rain deposition on a building. However, when results from the literature, our own measurements, and recent computer modeling [6] are evaluated in terms of DRF and RAF there is a reasonable agreement of results. Figure 1 shows that the amount of driving rain deposited on a building is usually less than the amount in the free wind (RAF<1),

although there may be small areas near the upper corners of the building where the RAF occasionally exceeds 1.0.

Peaked roofs and overhangs redirect airflow and can thereby have a significant effect on rain deposition (regardless of the building size). For example, adding a 1.5 m wide canopy to a multi-storey building will result in a lower RAF value and can, in theory, be an effective and economical means of improving rain control.

The increase in windspeed with height can be described by a power law (e.g. NBCC). Based on Equation (2), the upper portions of a 30 storey (78 m) apartment building would be exposed to almost twice the amount of rain wetting as a two-storey (5 m) house. When the sheltering effect of neighbouring houses and roof overhangs are taken into consideration, the rain on the low-rise building would be expected to be substantially less. Therefore, it should be clear that materials and assemblies suitable for low-rise buildings may not be suitable for high-rise buildings.

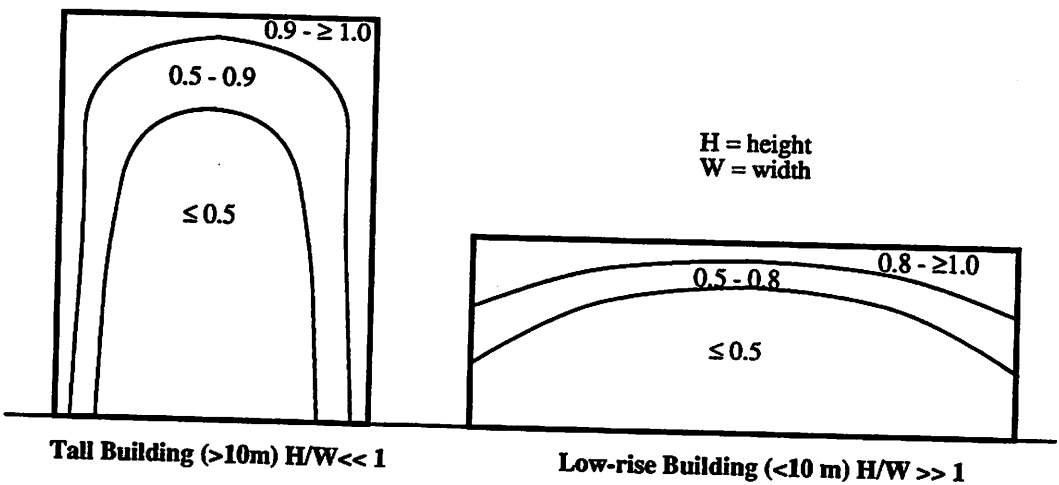


Figure 1: Typical RAF Values For Rectangular Buildings

Seasonal and Climate Effects

To assess the influence of climate on driving rain exposure, designers have resorted to Boyd's driving rain map of Canada [7] which is a plot of the Driving Rain Index (DRI). The DRI is the product of the annual average windspeed and total annual rainfall. (New, more detailed information is now available [8,9]). For lack of better information, the DRI assumes that both the windspeed during rain and wind direction during rain are the same as those during average conditions. While it can be shown that the distribution of windspeed during rain is almost the

same as that during all hours [1,9], the wind direction during rainfall is usually quite different than during non-rainy hours.

Figure 2 is a plot of the measured directional driving rain index for Waterloo. The plot was produced by multiplying the average windspeed and rainfall for every 15 minute period over the period of April 30 to Oct. 31, 1996. It can be seen that the amount of driving rain from the east is almost twice the average, while that from the north is less than one quarter the average. Thus, exposure to driving rain can vary by a factor of more than eight depending on the orientation of the building. More detailed analysis shows that the direction of driving rain also varies on a seasonal basis, and that high intensity rainfalls may come disproportionately from one direction.

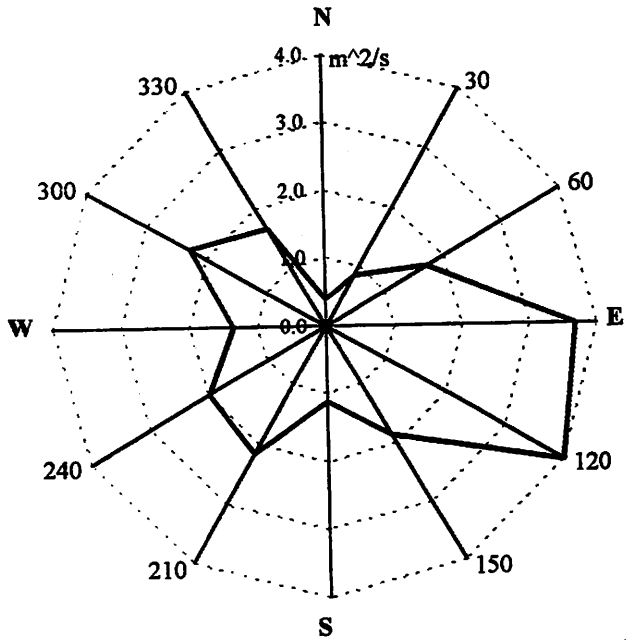


Figure 2: Directional Driving Rain Index for Waterloo, Ont.

A Wall Classification System

To provide a context and define the terminology used in the rest of this paper consider the classification system shown in Figure 3 which we have presented previously [10]. The categorization is independent of materials, building function, or design intent and is based solely on the method by which a wall system controls rain penetration.

Walls can be considered to be comprised of elements and the joints between these elements. Both the elements and joints may be classified in the same manner. The primary classification is whether a wall is a perfect barrier (often referred to as face sealed) or an imperfect barrier.

Perfect barriers stop all water penetration at a single plane, much as a perfect air barrier would prevent air flow. Some examples of perfect barrier walls are some window frames, and some metal and glass curtain wall systems. Because it is very difficult to build and maintain a perfect barrier wall, most walls are designed as, or perform as, imperfect barrier wall systems of either the mass type or the screened type.

Mass walls control rain penetration by absorbing and storing rain water which penetrates the exterior surface. In a functional mass wall this moisture is eventually removed by evaporative drying before it reaches the inner surface of the wall. Some examples of mass walls include adobe, solid multi-wythe brick masonry, and single-wythe block masonry.

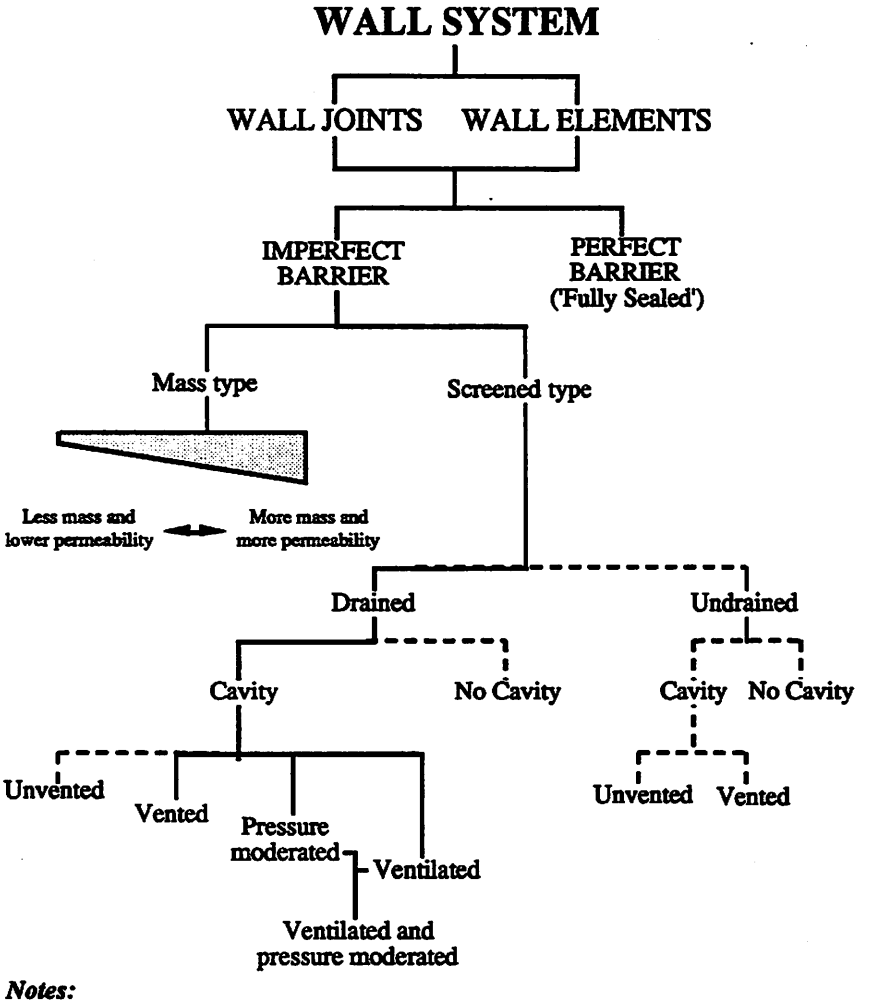
Screened walls are also imperfect-barrier type wall systems in that this approach acknowledges that some rain water will penetrate the screen. It should be noted that the screen is much more than a rainscreen; it must also resist wind, snow, solar radiation, impact, etc. The dashed lines in the figure indicate that, while undesirable, undrained walls do exist. Supplementary mechanisms, such as a capillary break and a water barrier, are usually employed to resist further inward movement of the water that penetrates the screen. Some examples of screened wall systems include cavity walls, brick and stone veneer, vinyl siding, two-stage joints, and drained EIFS.

A cavity behind the screen provides a capillary break, as well as a clear path for gravity drainage and a path for air flow. A cavity is defined here as any continuous space behind the screen, which may be filled with a porous material, that fulfills these functions. Given a cavity behind the screen, four major sub-classifications relating to air movement and vents are possible.

A *vented wall* system allows some degree of water vapor diffusion and air mixing between the cavity and the exterior. Venting (and, to a greater degree, ventilation) provides a mechanism for the removal of water that does not drain from the cavity. Venting, or better still, ventilation, may also remove water vapor that may have diffused outward from the inner wythe. By increasing the flow of air into and through the cavity, a relatively large volume of water vapor can be transported from the cavity. Such a *ventilated* wall will assist the drying of both the inner wythe and the screen.

A *pressure moderated* wall system promotes the moderation of the pressure difference across the screen. The proper choice of venting, i.e., size, number, and location, and the division of the cavity into stiff, airtight compartments are necessary requirements. Although such walls have heretofore been described as pressure equalized rainscreens (PER) in Canada, instantaneous pressure equalization rarely occurs in reality and the screen deals with more than rain — hence the more realistic term, "pressure moderated screened" (PMS) wall, is preferred.

A drained and vented screened wall that is both pressure moderated and ventilated is not only feasible, it should be the *preferred* solution for most applications.



Notes:

The walls are categorized based on actual behavior, not necessarily design intent.
For the purposes of this classification system, the following definitions are necessary:
Drained: the majority of the water that penetrates the screen is removed by gravity.
Cavity: a clear space or a filled space that facilitates gravity drainage and air flow and resists the lateral transfer of water (a capillary break).
Vented: allows some degree of water vapor diffusion through vents and by air mixing.
Ventilated: allows a significant flow of air largely to promote drying by mass vapour movement.
Pressure-moderated: an approach that moderates air pressure differences across the screen.

Figure 3: Wall Categorization System (by Rain Penetration Control)

Response to Driving Rain

Knowledge of the magnitude and frequency of driving rain can be used to define the rain load on a wall. As described in the previous section, different design strategies are used to control rain penetration. The response of different types of walls to deposited rain is examined in more detail below.

Drainage, Absorption, and Transmission

Rain deposited on a wall can either be face drained (shed), absorbed (by capillarity), or transmitted further into the wall. Each layer of a multi-layer wall responds in a similar manner. If water penetrates through the entire wall assembly, the wall is generally considered to have failed. However, transmission of rain water into any sensitive layer of a wall assembly may also cause damage, degrade performance and affect durability.

Wall response to driving rain can largely be described by the relative fractions of rainwater dealt with by each mechanism at each wall layer. Perfect barrier walls contain one layer where the fraction of rainwater transmitted inward is zero. A functional mass wall sheds or absorbs all rain water, thereby preventing inward transmission. Screened walls limit inward penetration by employing several layers (e.g., brick, air space, building paper), each with the ability to drain or absorb water. By reducing the amount of water transmitted at each layer, rain penetration control is achieved.

Different surface materials and textures will respond differently to rain that is deposited. For example, the majority of water falling onto a masonry veneer screen will be absorbed by the masonry during most rain events. If the masonry becomes saturated or the intensity of rainfall is high, rainwater will begin to be shed and transmitted through the veneer. A glass-and-metal curtain wall will respond quite differently. Shedding will begin very shortly after rain is deposited on the wall, and large surface flows of water can be expected during most rainfalls. Most wall systems' behaviour lies somewhere between these two extremes. For example, polymer-based (PB) EIFS absorb almost no water whereas cement-based (CB) stuccos behave like very thin masonry veneers.

Water Permeance of Masonry Veneers

The water permeance of an initially dry, well-built clay brick veneer has been tested in the laboratory under a range of conditions. The majority of the testing has been conducted with no air pressure difference imposed across the veneer. The fraction of applied water that was transmitted across, shed, and absorbed by the veneer in such a test is plotted in Figure 4. It can be seen that water penetration did not occur for more than 30 minutes even though water was applied at a rate of 3.33 $l/m^2/min.$, about 50 times what might be considered a "typical" rain

event! However, once the brickwork had become almost saturated, about 1.3% of the applied water penetrated. Despite the severity of the test, the amount of water transmitted through the veneer is so small, it can easily be drained by a properly designed and built assembly. If a more realistic rate of water were to be applied (e.g. 5 to 10 l/m^2/hr), water would not penetrate for a much longer period (because it would be absorbed by the masonry), the fraction that penetrated would be higher, and the rate of penetration would be much lower.

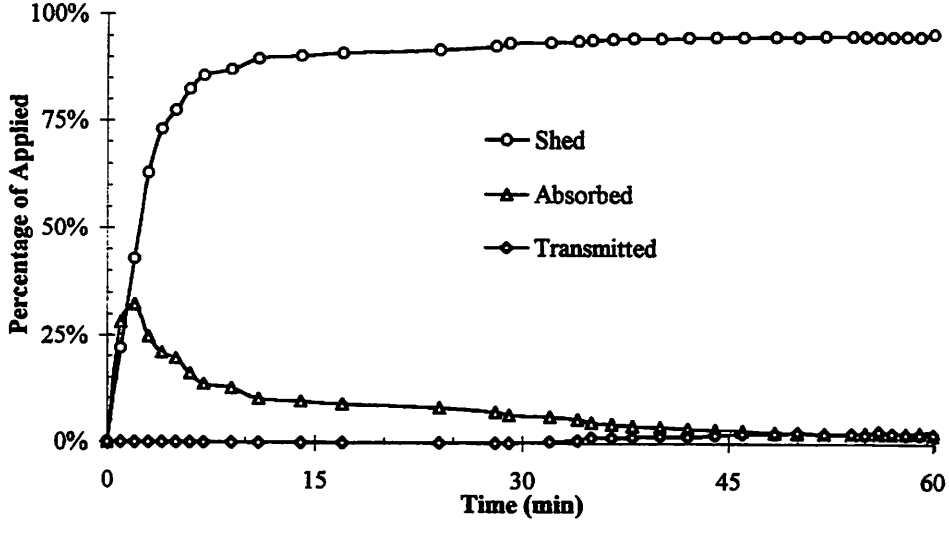


Figure 4: Water Permeance Test Results for a Brick Veneer ($\Delta P = 0$)

A literature review [11] of dozens of similar tests in the lab and in the field has shown that all brickwork veneers can be expected to absorb the majority of driving rain and, once saturated, transmit a significant fraction of the 1 to 3 l/m^2/hr typically imposed by driving rain. It has also been clearly established that water penetrates almost exclusively through the interfacial cracks between the mortar and brick at head joints. Capillary suction draws the water in (with pressures of up to 750 Pa) and gravity head within the head joints will drive the water out [5, 11].

Note that no air pressure was applied across the veneer in the test plotted in Figure 4. Although it is a commonly held belief that air pressure differences are the *primary* cause of water penetration of masonry veneers, there is little scientific support for this contention [11]. There are at least three reasons why this belief may have arisen. Air pressure differences *are* important for mass walls, such as multiwythe and TTW brick walls. Tests of curtain walls and windows also show that air pressure is often the most important penetration force for these perfect barrier systems. It has also often been observed that walls leak when it is very windy during rain. Only the last point is relevant to screened walls, but the observation of rain-wind-leak coincidence merely supports the fact that rain is deposited on a wall only when it is windy, not necessarily the assertion that wind pressure is the major cause of rain water penetration.

4.3 Wind Pressures and Masonry Veneer Permeance

Figure 5 is a plot of the steady-state (i.e. after at least an hour of testing) water permeance of the same clay brick veneer shown in Figure 4 as a function of the sustained air pressure differences. While large sustained air pressure differences clearly increase the amount of water penetration, water will penetrate even with a *suction* pressure applied. These tests demonstrate that water will always penetrate a brickwork veneer and, therefore, that a means of drainage behind the screen is always necessary.

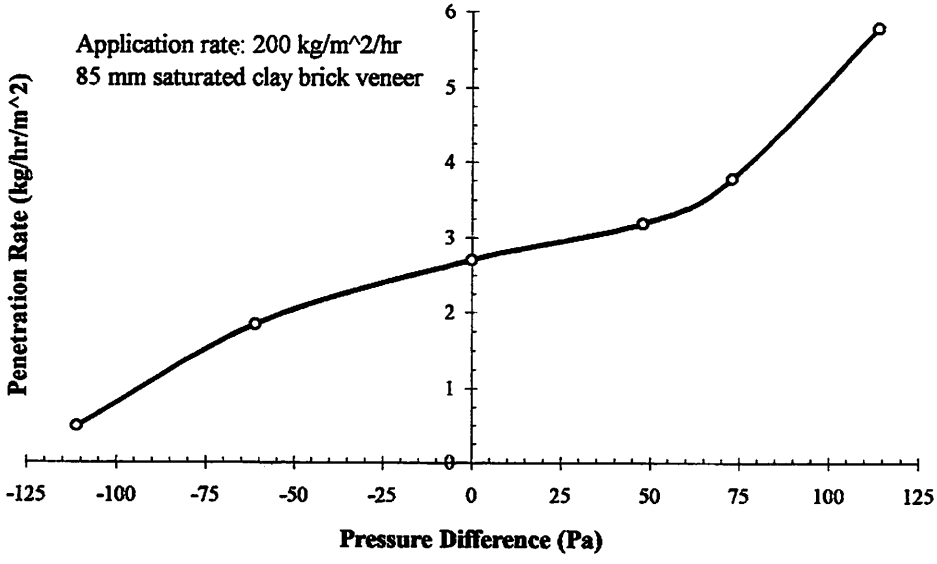


Figure 5: Steady-State Water Permeance vs. Air Pressure Difference

Although a 100 Pa pressure difference may not appear to be a large or even a significant pressure (compared to the pressures specified in design codes or standard tests), pressures of 100 Pa across the screen are actually unlikely. Average hourly wind speeds at 10 m above grade are in the range of 3 to 4 m/s. This wind speed will impose a pressure difference of less than 10 Pa across the envelope of a low-rise building. Even for a 50 m tall building in the suburbs the pressure will be less than 25 Pa. For 99% of the time the average wind pressure acting across the envelope will be no more than four times the average pressure (40 and 100 Pa respectively). Wind gusts longer than a few seconds can increase these pressures a further 50% (to 60 and 150 Pa respectively).

From the above it should be clear that it is quite unlikely that sustained wind pressure differences of more than 100 Pa will act across the envelope of most buildings most of the time. During the small percentage of time that high wind pressures act, it will be raining only during a small fraction of the time, i.e. the coincidence of rain and high winds are rare. In fact, the maximum

hourly wind pressure at 10 m during rainfalls reaches 250 Pa for less than one hour every 10 years in most Canadian locations [12]!

Screened walls (masonry veneers, vinyl siding, etc.) almost always contain a cavity vented to the exterior. Using basic orifice flow equations it can be shown that the average pressure acting across the *screen* (not the envelope) in a screened wall system will be less than 5% of the pressure across the envelope if the ratio of vent area to air barrier leakage area is more than about 5:1 [11]. This ratio of venting to leakage area can be achieved by masonry veneers built according to the masonry code or Part 9 of the NBCC. Therefore, for a properly-built vented veneer or cavity wall, the 1 hour-in-10 year 250 Pa wind pressure during rain would result in a pressure difference of less than 15 Pa across the screen.

Walls often perform poorly because design or construction errors result in systems that are much leakier or more poorly vented than the codes require. As a result of this poor construction, sustained pressures of 100 Pa may act across the screen, and in the case of masonry veneers, increase water transmission. Even so, the amount of water which penetrates the screen in most rain events will be so small that drainage, if provided, will remove it. Field monitoring by others has shown that typical brick veneer walls may moderate only 50% [13] and glass curtainwall spandrels may moderate only 25% [14] *of the static pressures* ! The lack of sufficient vent area, blocked air spaces, and leaky air barriers explain the lack of static pressure moderation in many typical walls.

Short-duration wind pressure variations (gusts) cannot be moderated as easily as sustained static pressures. Pressure-equalized rainscreen (PER) wall systems have recently received a great deal of attention. Based on lab tests which applied large sinusoidally-varying but spatially-uniform pressures [15] and simple computer models, requirements for air barrier tightness, venting area, air barrier stiffness, etc. have been developed [16]. These preliminary requirements are sometimes conflicting and can be difficult to implement in practice for some wall systems [17].

Field Pressure Moderation Measurements

BEG has been investigating the field performance of pressure moderated rainscreen wall systems for several years. Use has been made of the full-scale natural exposure and test facility, the Beghut, to measure the wind, driving rain, and the pressure response of several different wall systems in the field. The monitoring equipment constantly measures (at up to 16 Hz), the windspeed and direction and pressures at each vent hole, the middle exterior of the wall, and throughout the cavity.

Because the wind is by nature a random phenomenon, it can only be properly described using statistical measures. In fact, the apparently random wind shows repeatable and consistent

characteristics in the frequency domain. Different wind events can be more accurately compared, and the effect of frequency (i.e. gust speed) on pressure-moderation directly studied using frequency-domain analysis. An analysis method which provides a repeatable and meaningful description of the overall response of a pressure-moderated wall under a random and rapidly-varying wind force can be developed using wind engineering techniques [11, 18].

Our field monitoring has confirmed that high wind pressures, especially in conjunction with rain, are rare. The well-built wall systems monitored to date have shown a relatively high degree of pressure moderation over long time periods (more than five minutes), but very little pressure moderation of short term wind gusts. Figure 6 is a plot of the pressure moderation of a brick veneer wall (with a perfect air barrier and 4 open head joints, each 10 by 70 mm, venting a 2.4 m high and 1.2 m wide compartment) as a function of frequency (or, 1÷gust duration). The results indicate that pressure changes shorter than about 5 seconds long are moderated by less than 50% for wind directions nearly perpendicular to the wall. Note that these results are for a very well-vented, tightly-compartmentalized, very airtight wall near the middle of a building's face — typical masonry walls are likely to perform more poorly.

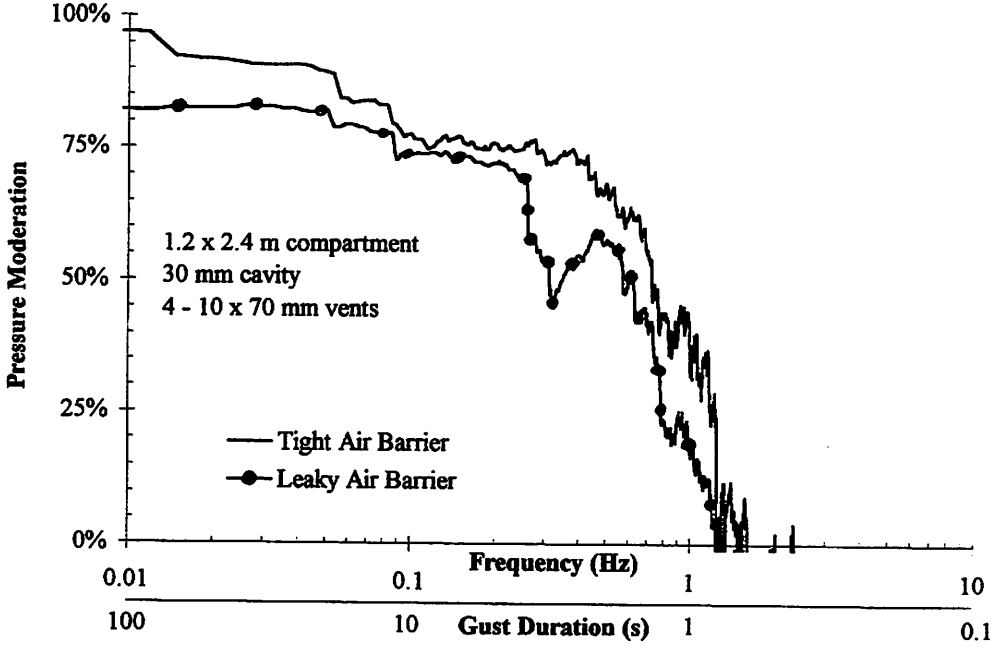


Figure 6: Pressure-Moderation Performance of a Brick Veneer Wall

A wall system similar to that monitored by BEG has also been tested in the lab [19]. Both this testing and computer modelling by BEG suggest that dynamic pressure moderation should be

about 95% at 1 Hz, whereas the field results show that the moderation is almost zero at this frequency. The primary reason for the lack of dynamic pressure moderation is the spatial variation of the wind pressure, i.e. there are pressure gradients across a building's face. The pressures acting at each vent opening can, at times, be quite different from the pressure acting at the center of a wall panel because of pressure gradients. The pressure in the cavity, however, responds only to the pressure at the vents. Therefore, while the wall plotted in Figure 6 may be able to quickly respond to temporal variations (e.g. lab tests, computer models), the spatial pressure variations (gradients) on the panel reduce the degree of moderation at high frequencies.

The results shown in Figure 6 are for a panel near the middle of a building. Detailed wind tunnel tests [20] show that the mean and instantaneous pressure gradients across the face of a building near the top and side edges of a building are much larger than near the middle. Therefore, dynamic pressure equalization will be much worse than that shown in Figure 6 for wall panels near building edges. In fact, the authors of Reference 20 recommend a maximum compartment size of 1 m^2 to achieve 80% dynamic pressure moderation. Even static pressure moderation will be negatively affected by the steep average gradients near edges. As shown earlier, the top and side edges are precisely where the majority of water will be deposited by driving rain.

Therefore, while the pressure moderation performance of a wall panel can be tested in the lab or predicted by simple computer models, the pressure moderation performance of most properly designed and built walls in service will be governed by spatial wind pressure variations, not the wall design or temporal wind pressure variations.

Although the characteristics of the wind will limit the maximum achievable degree of pressure moderation, wall characteristics will have some effect, especially at low frequencies. Also plotted in Figure 6 is the performance of the same test wall when a hole was opened through the primary air barrier. By increasing the equivalent leakage area to 7000 mm^2, the venting:air barrier leakage ratio was reduced to 2.5:1. The results show that static pressure moderation was reduced (to about 85%) and that the degree of dynamic pressure moderation was similarly affected. Note that simple theory predicts that a 2.5:1 vent:leakage ratio will result in a long-term (i.e. pseudo-static) pressure moderation of 84%.

Measurements of the same wall were taken with the vent area halved (by sealing two of the four vents). During one two week period only the bottom vents were open and during the next two week period one top vent and one bottom vent were left open. Comparison of the results in Figures 6 and 7 shows that the reduced vent area affects the pressure moderation performance to the almost same extent as the increased leakage area. Figure 7 also shows that the pressure moderation performance was similar regardless of the vent layout. Locating the vents at the top and bottom of the cavity has three distinct advantages however. First, the location of vents top

and bottom will allow much more ventilation drying to occur. Second, locating vents at the top is an easy and simple way to double the vent area so that more pressure moderation can occur. A third, more practical consideration is the fact that vents at the bottom of a wall are much more likely to be blocked by mortar than those at the top. It should also be noted that other research [2] has shown that almost all commercially available vent inserts drastically reduce air flow, and hence significantly reduce the effective vent area.

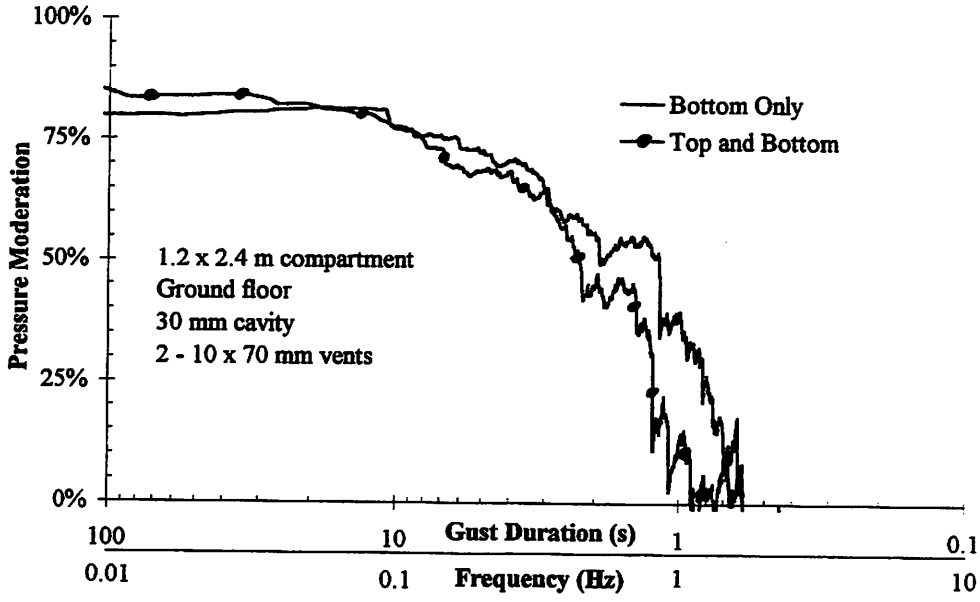


Figure 7: Pressure-Moderation Performance of a Brick Veneer with Reduced Vent Area

It can be concluded that pressure moderation performance is a function of both the characteristics of the wall and the wind. Even in walls compartmentalized at 1.2 x 2.4 m spacings, it is the spatio-temporal variations of the wind that will govern the performance of most pressure moderated wall systems. The spatial extent of gusts is likely the most important wind characteristic affecting pressure moderation, but the speed of the gust (i.e., frequency) and to a lesser extent, the magnitude of the gust, also play a role. Without very small compartments (less than 1 m^2) the degree of dynamic pressure moderation will be very low. Pressure moderation will be the worst at upper and side edges, the same areas of cladding that receive the most driving rain. Based on the available research, vent area appears to be the variable with the greatest influence on pressure moderation performance.

Discussion

A review of the literature and preliminary field measurements suggest that driving rain deposition rates of more than about 10 l/m^2/hour are only very rarely encountered, even on tall buildings. A number of researchers have found that the majority of driving-rain events can be expected to last for less than 6 to 10 hours (see [1, 5]).

These measured rates and durations can be compared to the application rates specified in ASTM standard tests for mass walls (e.g., E514: 139 l/m^2/hr for 72 hours) and for perfect barrier walls (e.g., E331: 204 l/m^2/hr for 15 minutes). The high rates used in standard tests ensure that a film of water forms on the surface before the cladding becomes saturated and thereby allow *relative* permeance to be measured without allowing the results to being influenced by the storage capacity of the cladding. The actual in-service behaviour of wall systems exposed to driving rain will, however, vary enormously depending on the nature of the shedding and absorption characteristics of the screen.

Most modern enclosure walls are screened and drained, i.e. they are designed with the expectation that rainwater will penetrate the screen. Therefore, the water permeance measured in standard tests is only of secondary importance since drainage is provided. The more important issue, not addressed by any standard test, is the ability of other layers in a wall system to drain water that penetrates. It can be observed that many reported rain penetration problems are in fact drainage failures.

Although the pressures applied across walls in standard tests tend to be too high, this is not significant for screened walls if the pressure is applied across the entire wall system, not just the screen (e.g. static pressure moderation is allowed to function). Dynamic pressures applied in dynamic lab tests and computer models obviously do not properly reflect actual field conditions because they are spatially-uniform . While relative differences in the dynamic pressure moderation of temporal pressure variations may be measured by dynamic lab tests or computer simulations, the pressure moderation performance in service will often be governed by the spatial variations of the wind pressures acting on the envelope.

Conclusions

Moisture control in above-grade walls is best achieved by the proper selection of materials and design of assemblies so that both storage and a drying potential higher than the wetting potential are provided. Because of the magnitude of driving rain deposition, rain control should be an important part of a moisture control stategy for the above-grade building envelope.

Ensuring controlled shedding from the face and unrestricted drainage from behind the screen are the two most important aspects of rain control in screened walls.

Attempting to build a waterproof masonry veneer is impractical, unnecessary, and uneconomical. Screened walls should provide a drainage system to deal with water that passes through the screen. Provided this drainage system can handle a few litres of water per hour during a few events per year, the water permeance of the screen is not a critical consideration. Therefore, ensuring a clear cavity, proper ties, good flashing, and unobstructed weep holes must be the priorities during design and construction.

The rain control of all types of screened walls can benefit from appropriate amounts of venting and the resultant high degree of static pressure moderation. Vent areas and air barriers must be provided as designed or pressure moderation performance will be reduced, sometimes significantly. Spatial pressure gradients will further reduce pressure moderation performance at the upper and side edges of buildings, the same areas of cladding that receive the most driving rain.

The rain control performance of masonry veneers can be improved only marginally by dynamic pressure moderation because:

1. mechanisms other than air pressure are the primary cause of water leakage through masonry,
2. drainage behind the veneer is critical and so must be provided anyway, and
3. pressure moderation of gusts is practically very difficult, primarily because of the spatial variability of wind pressures.

The abilities of a screened wall to absorb moisture and drain water that penetrates are critical characteristics; neither is addressed in existing ASTM or CSA test procedures. Standard water penetration tests impose unrealistically high pressure differences and driving rain rates. Standard tests have limited use for screened wall systems since they do not measure the critical rain control feature of this type of wall system: drainage.

Acknowledgments

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Retrofitting with Rainscreen Exterior Insulation Finish Systems

by Paul Duffy, M.A.Sc., P.Eng. [1]

KEY WORDS:

Cladding, Exterior Insulation Finish Systems, (EIFS), Pressure Equalized Rainscreens, Quality Assurance, Rain Leakage, Rainscreen, Recladding, Repair, Retrofit, Stabilization, Stucco, Walls.

ABSTRACT:

The practice of retrofitting existing buildings with Exterior Insulation Finish Systems (EIFS) is becoming increasingly common. Improved aesthetics, thermal resistance, rain penetration resistance and occupant comfort can be but a few of the benefits prompting such an upgrade. Newer "Rainscreen" versions of EIFS Systems have gone a long way towards solving some of the inherent problems with such retrofits, but, proper preparation, detailing and quality control are essential to ensuring the anticipated benefits are achieved. Cost considerations, design limitations and pre-existing problems may greatly limit the extent to which a solution can be thoroughly implemented.

As with any retrofit project, there are a number of key considerations that should be accounted for at the pre-design/investigation, design, and construction phases. Rainscreen EIFS Systems are relatively new so design experience and the information available from manufacturers may be limited. Based on preliminary experience with several innovative Rainscreen EIFS retrofits, a number important guidelines can be suggested. This paper provides detailed guidelines on use of materials, design considerations and quality assurance requirements at each phase of the project:

- Pre-design investigations should attempt to assess the structural adequacy of the existing wall, feasibility of creating a proper air barrier, attachment of EIFS elements, detailing needed to address issues of water penetration and condensation within the wall (i.e. behind the EIFS), as well as within the EIFS System.

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- Design detailing should attempt to provide redundancy of sealing at joints and transitions to other Systems (e.g. windows and roof), stress relief at areas of concentration (e.g. around windows, mechanical penetrations, etc.), extra abrasion/mechanical damage resistance at grade, and features to shed water from the outer surface.

- Construction quality assurance can then focus on proper application of materials during proper environmental conditions (wind/dust, temperature, rain), workmanship, adherence to specifications, details and related issues.

- Maintenance will primarily include a periodic review of the System along with periodic caulking replacement.

Many manufacturers are now offering extended warranties (10 years or more) on the performance of their Rainscreen EIFS Systems. This appears to be a way of encouraging building owners and managers to employ these more expensive Systems in their building retrofit/upgrades. It also is creating expectations that such Systems will achieve high levels of performance. Adhering to the guidelines identified in this paper are essential to assuring that performance expectations are met.

INTRODUCTION

Canada's building stock is aging. Many buildings, particularly those built in the 1970's and 1980's with inadequate attention to control of air leakage and wind driven rain, have reached a point where recladding must be considered.

Recladding with an EIFS Rainscreen System is an appealing alternative for rehabilitating the facades of older buildings. It provides significant design flexibility to upgrade both the appearance and performance of building envelopes. Based on experiences gained from some of the first buildings reclad with EIFS Rainscreen Systems, this paper attempts to identify and explain the rationale behind design, detailing and quality assurance procedures that were used.

Problems Warranting Recladding

Spalling claddings, staining, interior finish damage and structural failures are typical problems that may warrant recladding. Recladding provides the opportunity to address defects dating to the time of construction as well as problems that have accumulated as materials have deteriorated in the years since. Depending on detailing, the recladding work can act as a "band-aid" camouflaging ongoing deterioration, or alternately, it can correct and substantially slow processes of further deterioration. In some extreme cases, recladding over a rapidly deteriorating substrate has resulted

in unforeseen cladding failures. To avoid such an unfortunate circumstance it is desirable that recladding systems address, to the greatest extent possible, not only the problems themselves but also their root causes.

Problems such as spalling, staining and interior finish damage often occur as a result of moisture penetration. However, identifying moisture problems as a root cause is not enough. Moisture problems in walls can occur as a result of wind driven rain, wicking from poorly drained cavity wall systems, moist air leakage and/or concealed condensation. Measures that address wind-driven rain may be totally ineffective or even aggravate concealed condensation problems.

Leakage problems also are often related to structural problems and vice versa. Inadequate control jointing, long term creep of materials, thermal and moisture stress can all create cracks and gaps that are either problems themselves or they are related to problems of moisture penetration and corrosion. The movements may cause both cause attachment problems and cracking similar to that found in the original cladding.

Recladding over an existing cladding is tempting because it minimizes disruption and cost while providing improved aesthetics and marketability of buildings. Given the concerns outlined above, however, prudent design would suggest the need for a preliminary examination of the building that determines the feasibility of recladding over existing elements. Such preliminary examinations should assess:

- the structural characteristics of cladding elements, their attachment and suitability as a substrate;
- the performance of related elements (windows and roofs) and their contribution to known problems;
- additional loadings and attachment points of new cladding elements;
- opportunities for providing improved thermal performance, a continuous air barrier, vapour barrier, Rainscreen design.

It is precisely because they offer the potential to address fundamental building flaws that EIFS Rainscreen claddings hold appeal as key recladding alternative.

Attributes of EIFS Rainscreen Claddings

EIFS offers considerable architectural flexibility in terms of: colour, profile, surface texture, and relief. With the advent of EIFS Rainscreen Systems it is much more feasible to incorporate proper

building science detailing including an air barrier, cavity drainage and staged joints. Thereby the cladding can have multiple lines of defense against moisture problems.

Insulation at the core of the Systems provides thermal protection of structure, light weight and a versatile inorganic substrate for the thin veneer, acrylic stucco coating. Thermal bridging is minimized and inner wall elements can be largely protected from freeze-thaw cycling.

Several manufacturers are now purporting to sell Rainscreen EIFS Systems. A typical System configuration is shown in Figure 1. Depending on manufacturer and System chosen, Systems vary in terms of the following characteristics:

- Substrate: Some manufacturers allow their Systems to be placed over moisture sensitive substrates such as exterior grade gypsum board.

- Air Barrier Adhesive: Typically, the substrate is covered with a full layer of air barrier adhesive. Depending on manufacturer, the air barrier adhesive might have a low vapour permeance or alternately it may "breathe".

- Insulation: The insulation products typically used in such Systems include expanded polystyrene, extruded polystyrene and end bonded mineral fibre board.

- Drainage Scheme: The drainage scheme might be through the insulation as with mineral fibre, or through grooves cut into the back plane of the insulation. Some Systems are even using vertical grooves created using a "notched" trowel though the Air Barrier Adhesive; this can be quite susceptible to workmanship.

- Coating: Coatings are usually proprietary, though high impact resistance and non-combustible EIFS Systems (designed for use on buildings in excess of 6 storeys) generally incorporate thicker coatings. Design for non combustibility may also involve use of non combustible insulation and/or non combustible vent closure blocks in the drainage scheme. Most Systems consist of at least two coats: a base coat, into which glass fibre reinforcement mesh is imbedded, and a finish coat, containing pigments and texturing elements.

- Accessories: Accessories include compatible caulkings, air barrier transition membranes, flashings and foam sealants to provide air barrier continuity at joints and drainage to the exterior.

Depending on manufacturer and System chosen, a Rainscreen EIFS System may be a Draining System only providing paths for draining water out of the System. Alternately, it might be more

elaborate incorporating closures at regular intervals (e.g. every 10 m (30')) designed to provide true Pressure Equalizing Rainscreen (PER) performance.

Retrofit Design Objectives

Especially with PER Systems detailing can get complicated. In retrofit situations, detailing must account for many pre-existing and problem conditions specific to the building in question.

Depending on the outcome of the preliminary investigation, structural stabilization may be required before any recladding can proceed. This may involve:

- removal of failed elements,
- structural reinforcement,
- tiebacks to elements that are structurally sound,

Alternately, if the work is being undertaken over a substrate that is still structurally sound, very little work may be required.

Detailing to enhance moisture protection of interior elements should be included in the design. Complimenting the moisture protection offered by the Rainscreen design, it is desirable to include:

- "drip" edges to throw water clear of vertical surfaces (e.g. over windows),
- pan flashings to catch water leaking through window frame elements,
- cornices and mouldings to shed water,
- and flashings at parapets and projections.

To achieve air barrier continuity it may be necessary to provide:

- Foam sealants or caulking to fill gaps at control joints and transitions to other Systems: foam sealants will thermally isolate elements such as window frames; caulking is more appropriate if a flexible sealant is required; care is needed to avoid getting finish coating in caulked joints as it interferes with bond;
- Transition membranes at larger air barrier joints: Such membranes can be incompatible with some materials so surface preparation may be required;
- Tie ins to roof air barrier schemes to avoid air leakage into parapets; and

- Box-outs and/or flashings to finish around mechanical penetrations.

Proper design details aimed at ensuring satisfactory performance can add visual interest and add to the aesthetic improvements provided by the textural and colour changes inherent to the EIFS.

The complexity of the building, the pre-existing conditions and design objectives will dictate the number of design details that require special attention.

CRITICAL ISSUES WITH RAINSCREEN EIFS RECLADDING

Any recladding project faces a number of constraints as a result of working on an existing versus a new building. For example, window characteristics, locations, clearances, and drainage schemes can present a significant design challenge.

Other constraints are dictated by System characteristics. EIFS is temperature sensitive, usually site applied and subject to the skills of the applicator. To achieve a lasting result, proper procedures are needed at each stage of the design development and recladding process.

Design Detailing

Usually, the design process on an existing building represents a trade off between ideal concepts and less-than-ideal base conditions. Manufacturers can be of great assistance in solving difficult detailing problems, but, frequently, contractors are only provided with only the "simple" details such as a basic through-wall section, supplemental reinforcement at windows and doors, and terminations at parapets and control joints.

Usually, on an existing building reclad with EIFS, windows and doors become inset. One can elect to simplify detailing problems on the exterior by either replacing them at the same time or altering their positioning in the opening; frequently the cost of such measures is prohibitive. If existing windows are not moved, wrapping EIFS around the window and door insets can interfere with their operation. Poor termination of the EIFS can also create joints vulnerable to leakage.

To maintain the integrity of the air barrier at windows and doors, it is most desirable that a continuous seal be created linking the air barrier adhesive of the EIFS System to the window or door. Transition membranes—so called "peel and stick" materials are typically used for this purpose. Such materials usually have a bituminous core that will "bleed" if exposed to sunlight so it is necessary that they be covered by either the EIFS panel or by caulking. The combination of a

small projection of EIFS coating and transition membrane can position the caulking so that it interferes with window hinge assemblies. See Photo 1.

A compartmentalization scheme for each facade of the building is fundamental to the performance of PER - EIFS Systems. Typically, compartments will terminate at control joints, windows, projections and approximately every 10 m (30') coinciding roughly with logical break points such as floor slabs, column lines, window openings etc. All joints, changes in plane and penetrations should be detailed with compartment closures.

Parapets can be a concern visa vis ongoing deterioration. If the air barrier for the new wall System is not connected to the roof air barrier, a leakage path may exist within the parapet; concealed condensation and freeze-thaw cycling may result in continuing damage. See Figure 2.

All details should be reviewed in terms of how they might affect the post-retrofit performance of the building. For example, the improved air barrier and thermal performance of the EIFS System may emphasize the thermal bridging that remains after the retrofit. Poor windows often become more noticeable.

Given the fact that many Canadian designers have historically tended to base their envelope designs for large buildings based on masonry or precast, it is clear that a "learning curve" is involved in adapting to using an EIFS Rainscreen System.

Specifications

Manufacturers can be of particular assistance in developing specifications for a project. However, they will generally tend to encourage the use of specifications that limit product acceptance to their particular products. Unless a particular supplier is desired, care should be taken to ensure the specifications are as generic as possible. Fundamentally, it will be necessary to indicate whether a Draining or PER System is needed. Specifications for EIFS Systems also tend to require:

- compatible products (e.g. air barrier adhesives, transition membranes, insulation, mesh, base coat, finish coats and sealants from one System supplier;)
- proper application procedures and experienced applicators (e.g. Exterior Insulation Manufacturers Association (EIMA) Certification, five years experience with EIFS and specific training on Rainscreen Systems is often required;)
- suitable environmental conditions (above 5°C temperatures, no rain, low wind, avoidance of direct sunlight conditions)

- quality control procedures as required for manufacturer's warranties.

Beyond the specification of elements specific to a particular EIFS System, a variety of Systems may be specified on a given project. For example, as a way of maximizing value-for-money it may be seen as advantageous to specify:

- a particular EIFS Rainscreen System for the bulk of the building envelope;
- a System with extra reinforcement for areas subject to mechanical abuse (e.g. around balconies and close to grade;)
- a non-Rainscreen System for non critical areas (mechanical penthouses, canopies, etc.

Particularly on large buildings, this assists in making the work more cost-effective. It also adds to the complexity of quality control tasks.

Tendering and Contracts

Most manufacturers require that field applicators be experienced and properly trained for a warranty to be offered. Pre-qualification of contractors will assist in meeting these requirements.

Retrofit work by its very nature exposes unforeseen conditions and hidden problems. While lump sum or upset prices may be desirable as a way of controlling budgetary risk, unit pricing should be negotiated and contingencies should be carried for variable items such as structural repairs, air barrier repairs, coating of additional surfaces etc.

Many Systems/manufacturers also envisage that an additional contract be entered into to provide third party quality assurance on application of System elements. They will typically be able to provide a list of trained individuals / firms qualified to undertake such work.

Quality Assurance During Construction

The nature of the quality assurance work typically should involve:

- review of substrates and pre-existing conditions
- review of the application of each element of the System to help ensure manufacturer's guidelines were followed;
- tracking of batch numbers as required to assure consistent quality and finish;
- assistance in identifying and solving detailing problems;

- tracking use of Rainscreen and non-Rainscreen elements, as well as areas of extra reinforcement;
- maintenance of a photographic record.

Often on large projects, this individual or firm can be the only link helping to assure consistent practices are followed throughout construction.

STRATEGIES FOR ACHIEVING REQUIRED QUALITY

The experience from the initial group of buildings retrofitted with EIFS Rainscreen cladding Systems suggests that knowledge gaps may exist in the application of Systems because they are relatively new. Understanding the nature of the gaps that exist will assist in defining strategies for avoiding problems.

Strategies at the Pre-Design Stage

Typically, there is pressure at the pre-design stages to minimize cost as a way of financially justifying recladding. Frequently, it is assumed that existing claddings are structurally sound and suitable as an attachment substrate. Often this is not the case; the very problems that necessitate recladding are reasons why existing cladding is not suitable as an attachment substrate. Cut tests and hammer tap surveys are useful methods of determining the structural soundness of masonry and concrete. Wall ties and shelf angles should be visually reviewed.

A wall that outwardly looks structurally sound can be deceiving. In one case, an high-rise masonry wall that looked structurally sound was found to have spalled backwards into the wall cavity. Long term exfiltration of moist air, condensing on the back face of the masonry, had resulted in freeze thaw damage and decay of up to two thirds of the thickness of the masonry units in places. See Photo 2.

A decision to remove the existing cladding and reclad using EIFS may precipitate a number of measures needed to make the wall suitable for the application of EIFS Systems. Items to be addressed might include:

- Structural repair of the wall: often shear walls and back-up walls in older buildings will have been constructed using non-air-entrained concrete; freeze thaw damage can be severe. In reinforced block walls, improper placement of reinforcement bar, poor grouting procedures and inadequate structural design may necessitate structural repairs.

- Filling of gaps: Block back-up walls can be particularly porous. To form an air barrier, it may be necessary to fill horizontal and vertical joints and gaps. In most wall types, large gaps and spaces will exist around windows and other penetrations.

- Leveling of the substrate: removal of face brick often exposes forming errors dating back to the time of construction. Such errors are often camouflaged by varying the cavity width between the veneer and the back-up wall. In addition, to control thermal bridging, it may be desirable to remove slab-edge projections and other features that might interfere with placement the EIFS on a flat substrate.

- Temporary and/or permanent support of some features: The support conditions for many building features including balconies, windows and mechanical grilles will often have deteriorated; in one building a significant number of balcony slabs were found to be supported only by the veneer brick.

As painful as it may be, a thorough up-front investigation represents the best defense against unforeseen surprises.

Strategies at the Design Stage

The importance of thoughtfully developing the compartmentalization scheme has been previously discussed. Most Rainscreen Systems have been developed based on laboratory mock-ups of individual test panels. Fabrication of the edges and back planes of such panels can be relatively straightforward. As such, a sealed compartment is easier to achieve than it is in the field.

The sealing of the compartment where the base coat of EIFS connects to the air barrier back plane is particularly difficult to inspect; for this reason it is recommended that the detailing of this feature include a sealant applied at depth into joints to both provide a secondary seal at control joints and complete the closure of compartments. See Figure 3.

Compartment weep holes, drains and vents should be detailed with a positive slope out of the joint to promote drainage.

The fundamental nature of a Rainscreen EIFS System provides multiple lines of defense against wind-driven rain. Often the philosophy is not carried through to the detailing of other aspects of the retrofit. Staged joints should be provided at windows, mechanical penetrations, etc. See Figure 4.

Strategies at the Construction Stage

At the construction stage, the relative novelty of the Systems creates a need for close supervision. Some problems will have to be solved from first principles.

There are critical aspects to the application of most features of EIFS Rainscreen Systems. For example:

- Air Barrier Adhesives are generally rigid and will not bridge cracks and gaps over joints where movement is expected. The location of such joints must be carefully noted so that flexible seals can be provided.

- Transition Membranes often do not adhere well to air barrier adhesives though they may come from the same supplier. Primer is usually required but often not used.

- Base Coats must be tied in to the air barrier to fully seal a compartment. As previously mentioned, this is difficult to inspect so a perimeter sealant bead may be required. Proper environmental conditions are critical to achieving satisfactory performance.

- Reinforcing Mesh must be fully imbedded in the base coat. Protruding mesh may cause weak spots in the coating and interfere with finish and caulking application.

- Finish Coat consistency—batch colour and texture is assured by means of numbered batches from the manufacturer. Particularly on large jobs, batch numbers and applicators require close monitoring.

- Sealant bond can be adversely affected by the presence of Finish Coat on the surface to be sealed. Such areas may have to be masked or ground to achieve a suitable substrate for caulking. Further, caulking contractors typically unfamiliar with vented EIFS System frequently inadvertently conceal vents with caulking.

Qualified third party review greatly assists the pursuit of quality particularly at the construction stages.

Initial experience suggests that buildings retrofitted using EIFS Rainscreen Systems will essentially solve thermal and moisture problems if thorough processes are carried out. On one of the buildings, flood testing and rain storms, that occurred before and after final caulking was carried out, has confirmed that proper application of EIFS Rainscreen System has essentially solved a severe wall leakage problem.

CONCLUSIONS

The experience with the initial buildings retrofitted using EIFS Rainscreen Systems provides a good news / bad news story for building owners considering recladding options.

Myths Regarding EIFS

Proponents of EIFS often suggest that it is a cheap alternative to brick cladding. From the initial buildings, this does not appear to be the case as far as the Rainscreen Systems are concerned. It is comparably priced however and the EIFS offers technical advantages that include:

- light weight,
- significant increases in insulation levels,
- thermal protection of structural elements, and
- design flexibility.

Detractors of EIFS suggest it is very sensitive to workmanship and prone to leakage problems and deterioration. This too is a myth in that the Rainscreen Systems address many of the historical technical issues related to EIFS. The resultant Systems have multiple lines of defense similar to cavity wall and other masonry systems. Design and construction expertise is required; the expertise required is comparable to that required for other Rainscreen wall types.

Minimum Requirements

Based on the positive results that have been achieved, if EIFS is being considered as a cladding option, a Rainscreen System should be used. Recognizing that experience with such Systems is limited, EIMA Certification of the manufacturer and use of an experienced EIFS contractor with training from the manufacturer in the area of Rainscreen Systems provide useful starting points for qualifying product suppliers and applicators. Design and third-party review from qualified professionals will, in most cases, be necessary to develop suitable designs that are properly implemented for warranty purposes. Once the design is properly implemented, wall leakage problems should essentially be solved; long term maintenance can primarily be confined to a periodic review of the System along with periodic caulking replacement.

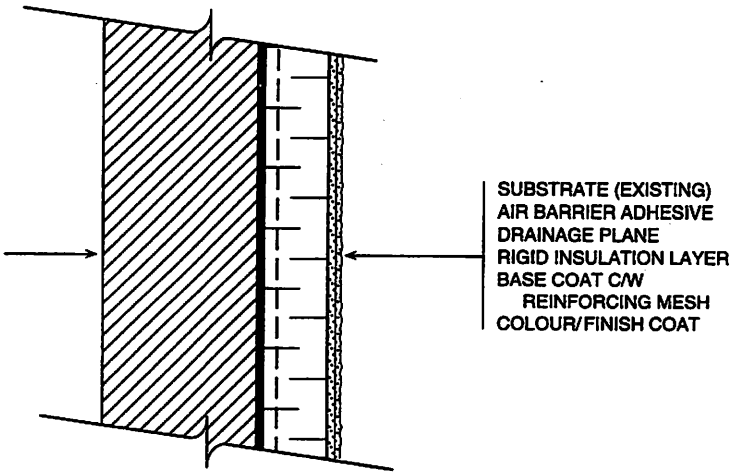

FIGURE 1: TYPICAL RAINSCREEN EIFS SYSTEM CONFIGURATION

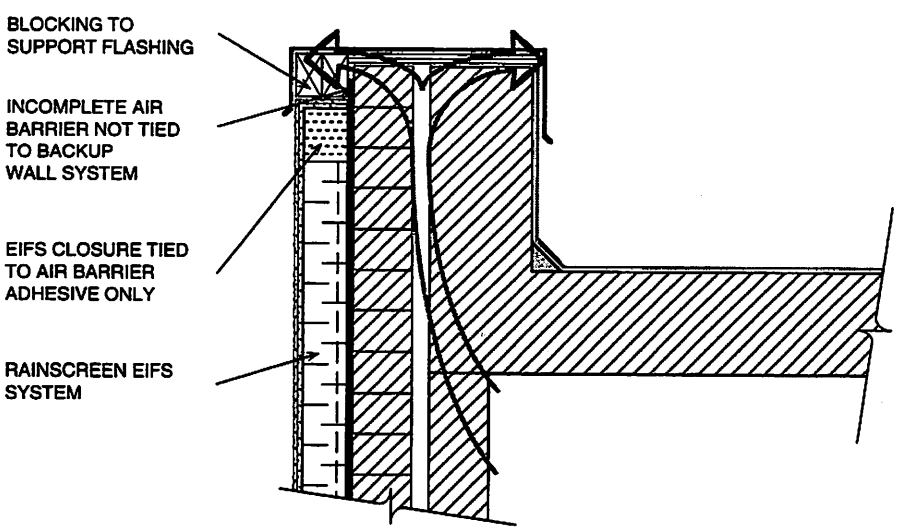

FIGURE 2: AIR LEAKAGE PATH EXISTS UP THROUGH
CAVITY BEHIND VENEER BRICK

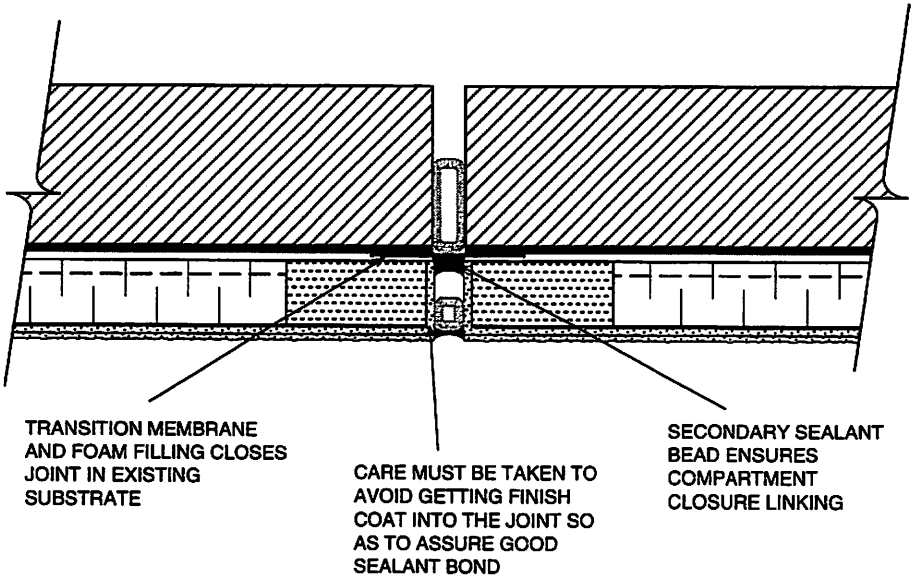

FIGURE 3: CONTROL JOINT DETAILING FOR REDUNDANCY

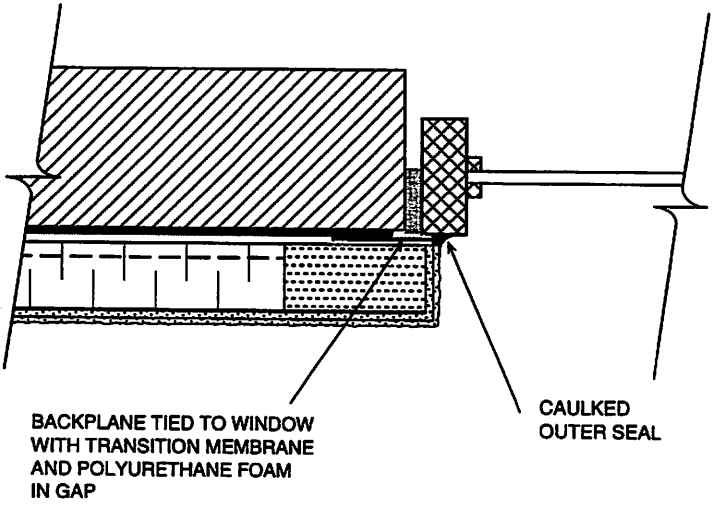

FIGURE 4: WINDOW DETAILING FOR REDUNDANCY

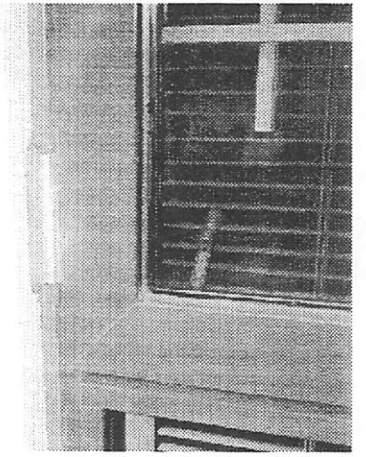

PHOTO 1: PROJECTION OF EIFS COATING / CAULKING INTERFERING WITH OPERATION OF HINGES OF CASEMENT WINDOW.

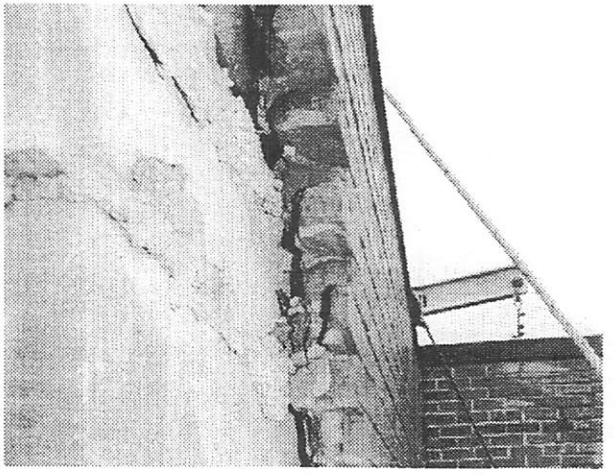

PHOTO 2: DETERIORATED BRICK CLADDING CREATES ATTACHMENT PROBLEMS FOR NEW CLADDING MATERIAL. NOTE: UP TO 2/3 OF THE THICKNESS OF BRICK HAD SPALLED INTO THE CAVITY.

Scan me

Distress of Stucco-Clad Buildings in the Vancouver Area

By Marcus Dell, P.Eng., Pierre-Michel Busque, P.Eng., Sean Liaw, P.Eng.[1]

Many stucco-clad structures have been constructed during the tremendous development boom the Vancouver area has experienced in the last decade. These structures range from high-rise buildings to small, single-family dwellings. An unusually large proportion of building owners are reporting problems with the performance of stucco-clad exterior walls. The problems most frequently reported include water ingress into the building, mould growth on the interior walls, cracked exterior cladding, staining of the exterior stucco, and structural deterioration of wood components (in the case of wood-frame buildings).

Because problems have become so widespread, it has been suggested that stucco should not be used as a cladding material in the Vancouver area. This suggestion may be valid — if it were not for the fact that stucco-clad structures built in the 1940s and 1950s typically outperform those built 5 years ago.

The number of stucco-clad building failures has prompted the City of Vancouver to publish a Bulletin which requires that a professional designer be responsible for the coordination of all building envelope subtrades, as well as for the site inspection of detailing, unless certain warranty program requirements are met.

This paper is a review of the factors affecting the durability of stucco-clad structures. The content of the paper is primarily drawn from the site investigations performed by Levelton Associates.

Key Words: Vancouver, rot, wood-frame, stucco, details

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Background

Since the mid-1980s, the greater Vancouver area has experienced substantial growth. The effect of this growth and the increased demand for affordable housing prompted the construction of a multitude of low-rise, multi-unit, residential buildings. Many of these buildings incorporate the same architectural features as buildings in the milder climate of southern California. One such feature is the use of stucco cladding.

The greater Vancouver area is experiencing an epidemic of stucco-clad-building failures. Many of the buildings which have failed are less than 7 years old. The repair costs are often greater than the reserves available to Stratas (the group of owners managing the maintenance/reserve funds for these buildings), and the additional funding levies cause undue financial hardships on owners. Discussed in this paper are the factors which have contributed to the drastic failures observed in wood-frame, three and four-storey, stucco-clad structures. Also discussed are solutions that have been implemented in remedial projects.

Water ingress and the resultant deterioration are also occurring in wood-frame structures clad in other materials, such a vinyl and bevelled siding. The problems and causes are similar, but will not be discussed in this paper. Similarly, the problems and causes of water ingress into high-rise buildings clad with stucco are beyond the scope of this paper.

General Description of Stucco-Clad, Wood-Frame Buildings

The stucco cladding systems on most wood-frame residential buildings can be separated into three categories: face-sealed, modified face-sealed, and rainscreen. Rainscreen stucco applications were rarely constructed on low-rise residential buildings until recently. The differences between these wall systems will be discussed further in this paper.

The standard stucco-clad wall system consists of the following, listed from interior to the exterior:

- Interior gypsum
- 4 or 6 mil polyethylene vapour barrier
- 2-inch by 4-inch or 2-inch by 6-inch wood studs with glass-fibre insulation between
- Exterior sheathing (plywood or oriented strand board)

- Sheathing paper (asphalt-impregnated organic paper or synthetic polyolefin)
- 21mm (⅞-inch) thick stucco application. Stucco applications should consist of three coats. The finish coat may be acrylic modified (in this case, thickness would be slightly less than 21mm).

During the standard construction process, the sheathing paper is stapled to the exterior side of the wall sheathing. Ideally, all the joints in the sheathing paper are lapped shingle style to direct water to the exterior. Typically, a 2-inch by 2-inch wire mesh is nailed to the exterior of the sheathing paper onto which the stucco is applied. This results in the stucco being tight to the sheathing paper. Nails used to secure the wire mesh and ancillary components result in numerous points of potential water penetration behind the sheathing paper.

In a face-sealed stucco application, all penetrations are fully sealed, and there is no provision made to allow water that penetrates the cladding to drain out. In a modified face-sealed system, all the penetrations are fully sealed but some provision is made to discharge water that drains down the building paper to the exterior. These points of discharge are at window heads, at floor lines, and at the base of the wall. For the purpose of simplicity, stucco walls not containing a drainage cavity will be referred to as face-sealed walls, and a rainscreen wall will be defined as a wall that incorporates a drainage cavity behind the stucco.

Deterioration of Wood

The majority of wood-frame construction uses Hemlock or Fir for joists and beams and S-P-F (Spruce-Pine-Fir) for studs. Either oriented strand board (OSB) or plywood is used as the exterior sheathing. S-P-F lumber has a moderate resistance to deterioration, while Hemlock and Fir have slightly better resistance to deterioration. The chips from which OSB is composed have a low resistance to deterioration. Plywood has a resistance to deterioration similar to Hemlock and Fir.

Brown rot is the most common type of decay fungi found on the West Coast. Dry rot is a commonly misused term; it is seldom found in the Vancouver area. Brown rot causes the wood to shrink and the surface to become dark and crumbly. Brown rot and the associated mycelia (white, stringy growth) are relatively easy to identify.

For fungi to grow, four conditions must be present: oxygen, moisture, warmth (5°C to 40°C), and a food source (wood)[1]. Typically, wet rot fungi require a wood moisture content of

approximately 28% to colonize. However, once started, colonization will continue at moisture contents as low as 20%. Ideal conditions for wet rot growth are approximately 20°C to 30°C and 20% to 60% moisture content in the wood. Under ideal conditions, rot can propagate in sapwood at a rate of up to 10mm per day. Heartwood is less prone to deterioration. The loss in strength that occurs as a result of decay fungi occurs before and beyond the visible signs of decay. Under ideal conditions, strength loss parallel to the grain in sapwood can occur at 15% to 40% per week.

Moisture Contribution to the Building Envelope

Most of the failures observed in the field involve water ingress and rot in the wooden components that make up the structure of the buildings. It is, therefore, relevant to discuss the sources of moisture loading on the building envelope. The principle factors responsible for moisture contribution to the building envelope have been well documented by agencies such as the National Research Council of Canada and Canada Mortgage and Housing Corporation. The following mechanisms and their relative impact on buildings in the greater Vancouver area will be summarily discussed.

Construction Moisture

It is very common for buildings to be erected while not being adequately protected from rain. Winter field measurements have found moisture contents in the framing and sheathing of 28% to 30% (wood fibre saturation). It is also very common for the cladding to be applied before these materials have had a chance to dry. If there is no ventilation space behind the cladding, the moisture trapped within the wall assembly will need to be expelled from the wall by diffusion through the exterior cladding. The rate of drying will depend upon such factors as the vapour permeability of the wet material behind the cladding and that of the cladding material, the outdoor temperature and relative humidity, and the colour and exposure to solar radiation of the exterior wall. Therefore, it is possible for buildings framed during the fall and winter rains to start to deteriorate before summer conditions allow drying of the walls.

Environmental Conditions

The climatic conditions on the southwest coast of British Columbia are unique in comparison with the remainder of Canada. Environment Canada defines the climatic region as a temperate rain forest; the average winter temperature remains above freezing, and the annual precipitation averages 1.3m[2]. It is not just the volume of rain, but also the continuity of the rain, that results in conditions conducive to the deterioration of wood-frame structures. This persistent rainfall does not allow for drying of the walls.

The frontal patterns result in almost all rain being associated with easterly winds. This is consistent with our field observations that the majority of the deterioration occurs on the east elevation and southeast corners of buildings.

Deterioration may also occur on north elevations of buildings that are constructed during wet weather. Because north elevations receive less solar radiation, drying is not as rapid as on the south and west elevations.

It is our observation that the majority of the deterioration in wood-frame buildings occurs as a direct result of the environmental conditions both during and after construction. Temperate rain forest climatic conditions provide the ideal environment for fungal decay.

Air Leakage

Mechanical pressurization of the building envelope, wind effects, and the stack effect are all well-documented phenomena. Driven by these forces, warm, moist interior air is channelled through openings in the building envelope, and moisture is deposited on colder condensation planes within the wall assembly. To counter this phenomena, the building envelope should incorporate an air barrier which is continuous, durable, structural, and of course, air-impermeable. The leakage of warm moist air outwards through the building envelope is less important in the greater Vancouver area than other colder parts of the country. Of the numerous moisture-damaged structures examined by the authors, none of the failures could be attributed to the outward leakage of interior air. However, evidence of water leakage through the exterior was significant in most of the deteriorated structures. It is possible that the damage caused by water ingress into the walls masked the damage caused by condensation attributable to air leakage. In concept, it is possible that condensation as a result of air leakage will provide adequate moisture to support fungi (20% moisture content), once the fungi has started to colonize.

Diffusion

A vapour barrier is used to retard the movement of moisture, by diffusion, contained in the interior air of a dwelling through the building envelope. It is located on the warm side of the insulation in order to prevent condensation from occurring on colder exterior components. Usually, a 6 mil polyethylene sheet is used to accomplish this task.

Deterioration of wood-frame structures as a result of condensation due to vapour diffusion has not been observed in any of our examinations. In fact, once water has penetrated the wall, the vapour barrier has a negative effect because it reduces the drying potential of the wall system. The rate at which walls dry is an important factor in the onset of rot.

Design and Construction Factors

Site investigations by the authors have uncovered the following building envelope deficiencies which are responsible for water ingress into wall assemblies. The deficiencies are listed in order of severity, from worst to least.

Window Leaks

In-situ testing of windows (ASTM E 1105 - *Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls, and Doors by Uniform or Cyclic Static Air Pressure Differences*) has established that improperly sealed mitre joints in the glazing pocket or the condensation track is a recurrent problem. Because of the standard method of installing the sheathing paper around the windows, water that leaks through the mitred corners can penetrate into the wall behind the sheathing paper.

An improper lap is often formed at the bottom corners of the windows. This occurs when the paper below the window is installed after the paper at the jambs. These improper laps direct water that is running down the jambs behind the paper below the window. The significance of an improper lap at the bottom of the windows is magnified by two other installation errors. Firstly, it is common for the window head flashings to be too short (not extended past the window jamb) and to be sloped inwards. These problems with the head flashings concentrate water at the junction of the building paper and the window jamb. Secondly, Section 9.27.4 of the British Columbia Building Code and the City of Vancouver Building By-Laws require the application of a caulk seal between the stucco and the window frame. This caulk seal is almost

never installed. The lack of a seal between the window and the stucco allows water behind the stucco. If the paper is improperly installed, water ingress occurs. Even if the paper is correctly installed, a face-sealed or modified face-sealed stucco system can not typically drain water penetrating behind the stucco.

Properly sloped horizontal head flashing that extends beyond the width of the window and ship-lapping of the building paper around the window flange are extremely important. To prevent moisture from leaking inside the window's rough opening and migrating into the wall, peel-and-stick membrane running from the wall sheathing into the rough opening is now being used. A window detail developed by the authors is shown in Figure 1.

Balcony Guards and Curbs

The junction of these components to the wall has been a problematic one for the construction industry. These details (commonly referred to as saddles) fail because they do not allow egress of water that is draining down the sheathing paper and because they do not direct water away from the tie-in. Often, the metal flashing on top of the guard or curb becomes dished, directing water into and behind the stucco on the wall. Figure 2 is an illustration of a properly designed saddle. Note that a complete membrane seal is implemented below the prefabricated metal cap flashings.

Expansion Joints

Expansion joints are used to reduce the cracking of stucco by limiting the size of a stucco panel. Designers often use a pattern of intersecting vertical and horizontal expansion joints to create visual appeal and to allow for colour changes in the stucco. Expansion joints are typically of the W-shape type. This practice is not recommended because water will penetrate the expansion joints at their intersections and at butt joints. Water can accumulate inside the expansion joints until it penetrates through anomalies in the sheathing paper.

Application of Stucco

The Building Codes require that stucco have a minimum thickness of 15mm (3/5 inch) measured from the face of the reinforcing wire. In-house testing has determined that the quantity of water that penetrates stucco through absorption (capillary action) is negligible, even if the stucco is

below the Codes' required thickness. Major points of water ingress are cracks in the stucco and poorly executed waterproofing at penetrations.

Improper curing of the stucco at the time of application can result in cracking; this typically occurs in warm weather. If the stucco is allowed to freeze while it is fresh, ice lenses will form within the material, resulting in a weak surface and poor weathering resistance.

The results of numerous cut tests have determined that stucco will bond to synthetic sheathing papers if applied directly on it. When the stucco is bonded to the sheathing membrane, water cannot drain down the interface between the two materials. The trapped water will penetrate at anomalies in the sheathing paper or eventually through the paper itself.

Application of the stucco directly on the sheathing paper is not a practice which is recommended. If water penetrates cracks in the stucco, it will migrate down the wall between the stucco and the building paper. Eventually, the water may find an imperfection in the building paper and penetrate the assembly. Many of the older stucco buildings constructed in the 1930s to the late 1950s have and will likely outperform those constructed today. One of the possible reasons may be the use of cedar strapping behind the stucco. This strapping helps to provide an air gap behind the stucco which helps the water which penetrates the stucco to drain out from the wall. It is not uncommon to find that the building paper used in these older buildings is in better condition after decades of use than is the building paper of the buildings which are the subject of this paper.

Wood shrinkage

A typical three-storey, wood-frame structure can be expected to shrink up to 9mm (2/5 inch)[3] per floor as the wood used during construction reaches moisture equilibrium with the indoor environment (assuming the wood was installed at 19% moisture content; more shrinkage will occur in buildings constructed with moisture-saturated lumber). Frame shrinkage can damage windows and can exceed the compression tolerance of W-shaped expansion joints. As most of the shrinkage occurs across the grain of the wood, improperly detailed stucco stops may be pushed away from the wall at floor end joists, creating a pocket between the wall sheathing and the stucco. Good practice calls for all vertical stucco stops to be discontinuous at floor lines. Through-wall flashings can be installed at the floor lines (secured to the centre of the trim joists) to accommodate the frame shrinkage without the use of horizontal control joints.

Buildings that are constructed with wood of an acceptable moisture content will shrink less, and are less prone to deterioration as a result of moisture trapped in the wall during construction.

Intricate Architectural Features

Intricate architectural features are used to entice the prospective buyer. If devoid of any functionality (unlike overhangs or cornices which help shed water away from the wall), they may actually become water traps which contribute to water ingress. In the Vancouver area, common problematic architectural features are plastic architectural reveals and the extensive use of curved projections on walls. Such features are problematic because they do not easily tolerate shrinkage of the wood frame, and cracks are induced by curing shrinkage of the stucco. If intricate architectural features are present on a building, it is paramount that the designer develops a water management strategy for them.

Lack of Through-Wall Flashings

Water will penetrate through defects in the stucco, at poorly designed and constructed penetrations, or through the stucco itself. The less distance the water travels before egressing from the wall, the lower the potential for water to penetrate anomalies in the sheathing membrane. Through-wall flashings are an effective method of draining water away from the walls at the floor lines while permitting the designer to address issues such as wood shrinkage.

Other

Stucco applications terminate at the base of walls with a stucco stop. These stucco stops are rarely filled during the stucco application, leaving a trough through which water can travel. Water from this source has been observed to penetrate into intersecting walls and columns, resulting in significant damage. Trapped water will also cause corrosion of the stucco stop, which, in turn, will stain the stucco.

It is now common practice to use stucco stops that have drainage holes. Stucco stops with pre-punched holes are now available, but our testing has determined that the pre-punched openings are not sufficiently large to overcome surface tension.

Scaffolding anchors are often left in place prior to the application of stucco. Cracks often develop around the anchors, allowing water to ingress. The water will corrode the anchors and

result in staining of the exterior face of the wall. Buildup of corrosive residue from the anchors will cause even more stucco cracking and, eventually, spalling.

Material Factors

Sheathing Paper

Asphalt-impregnated, D-grade building paper (commonly referred to as 10-minute building paper) and synthetic polyolefin sheathing papers have been extensively used in the Vancouver area. These sheathing papers offer a lower resistance to water penetration than the heavy-grade, 60-minute building paper. When stucco is exposed to rain for long periods, it may become saturated—absorbing up to 10% of its weight in moisture[4]. If the stucco is in contact with the building paper (which itself is in contact with the wood sheathing), there is excellent potential for the sheathing to absorb enough moisture to allow the growth of decay micro-organisms in the wood sheathing. Furthermore, if the stucco is exposed to warm temperatures and solar radiation, the temperature of the stucco will rise, thus, accelerating the fungal growth. The vapour pressure during the drying process will increase the diffusion rate of water vapour through the building paper and into the wood sheathing—elevating its moisture content. Because outdoor temperatures in Vancouver are milder than in the rest of the country, the use of a building paper that is less vapour permeable is considered desirable by the authors. Recently, in an effort to alleviate water ingress into stucco-clad structures, the City of Vancouver has mandated the use two layers of 30-minute building paper[4].

Wood Sheathing

Although plywood and OSB sheathing can absorb the same amount of water (on a weight basis), the structure of the OSB may facilitate the absorption of water (due to the fact that there is more exposed end grain). The wet cup permeability of plywood has been measured at 2000 ng/(Pa•s•m^2)[4], while the wet cup permeability of OSB has been measured at 500 ng/(Pa•s•m^2)[4]. This difference may be significant when considering the overall drying potential of the wall.

Another observed problem with OSB is that it swells when wet. Water-induced swelling of OSB is suspected of contributing to the cracking of stucco which, in turn, results in more water ingress — a synergistic problem.

Improvements

The following additional tasks must be undertaken to ensure the performance of stucco-clad, wood-frame structures.

Design and Detailing

A water control or water management concept must be developed at the time of initial design. If a complex configuration utilizing exposed walkways, sun decks, curved walls and windows, etc., is to be utilized, meticulous attention must be paid to the design and construction of the details. The designer must consider that the costs associated with this type of design will be high if a resilient structure is to be obtained.

The design must incorporate resilient construction materials. It is probable the walls components will be subject to moisture from rain penetration, air leakage, or condensation at some time during the life of the building.

The results of our investigations and field observations indicate that stucco cladding on wood-frame structures will not perform if it is a fully face-sealed system. It is not possible to stop water penetrating the building, unless a proper drainage cavity is utilized to drain water that has penetrated the stucco. An effective "rainscreen" system is required.

Some problems associated with designing a rainscreen system for wood-frame construction include:

- The thickness of the cladding system cannot be significantly altered if the presently available windows and doors are to be utilized.
- Many architects want the general appearance of the stucco to remain the same.
- A water-resistant material is required on the inside face of the drainage cavity. Because insulation cannot be easily installed on the exterior of the water-resistant material, the water-resistant material must be vapour-permeable. The water-resistant material must also be vapour-permeable to allow drying of any water accumulation in the wall system as a result of air leakage and/or vapour diffusion.

One method of creating a drainage cavity is to install a geotextile drainage layer between the sheathing membrane and the back side of the stucco. Geotextiles used to date have consisted of a cross-pattern, high-density polyethylene with a polyester fleece on the outer face. The total thickness of the geotextile is approximately 7mm, allowing it to be used with presently available

windows and doors without compromising the required thickness of the stucco. The sheathing membrane presently being used with the drainage layer consists of an asphalt-impregnated, heavy-weight building paper with asphaltic peel-and-stick membranes at select locations.

ASTM 1105 tests conducted under 250 Pa of depressurization across a wall that has not yet received stucco cladding have shown that water can penetrate the holes created when nails are driven through the sheathing paper to fasten the stucco lath. Therefore, the use of 50mm wide strips of asphaltic peel-and-stick membrane at 16-inch intervals over the sheathing paper has been adopted. As nails to fasten the stucco lath only penetrate the 'self-healing' asphaltic strips, the potential for water penetration behind the sheathing paper is reduced.

Through-wall flashings are required at each floor line to discharge water from the drainage medium. The placement of through-wall flashings at each floor line can also be used to accommodate frame shrinkage.

Perspective

Problems with stucco-clad structures are all too frequent in the greater Vancouver area. Such problems have enormous consequences because of the financial and sociological impact on the people who reside in these structures. The following three scenarios have been observed in the course of our practice.

Case 1

The renovation work needed to repair damage to an 86-unit condominium building was estimated in the $700,000 range. The owners decided to paint the building with elastomeric paint for the third time in 5 years in an effort to solve their water ingress problem. The owners ignored recommendations that the water now present in the walls be removed to prevent further deterioration of the wood-frame structure.

Case 2

Similar to Case 1, but the owners decided to repair the building 3 years after it was painted. Advanced structural deterioration of the wood frame had taken place. The cost of the ongoing repairs will be approximately $1.5 million over approximately 3 years.

Case 3

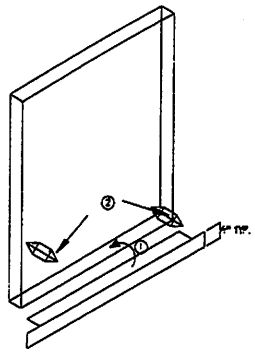
A three-unit condominium building leaked since its construction in 1991. The total repair cost was approximately $400,000.

Conclusions

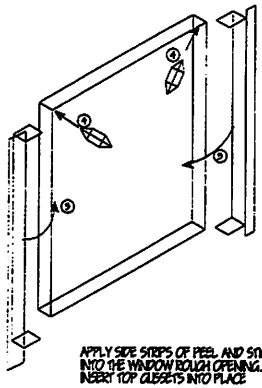
Through conducting numerous site investigations, it was possible to observe symptoms of air leakage in buildings. Such symptoms were usually not accompanied by damage to the building envelope and usually limited themselves to dusty carpets at the baseboards and dusty wall insulation. By contrast, the damage observed on wood-frame, multi-unit residential buildings was usually related to water ingress into the building envelope. Such damage can be extensive and, understandably, is a cause of distress among the owners of the buildings.

Design, supervision, and construction practices must be modified if durable buildings are to be constructed. Although Building Code issues still need to be addressed by the industry to improve the performance of stucco-clad structures, it is impractical to legislate and enforce good practice. There are many examples in the Vancouver area that prove stucco-clad, wood-frame structures can be designed and constructed to provide a responsible economic performance life, if the required level of care is taken. The dramatic failures that have occurred in greater Vancouver clearly indicate that the design and construction practices of the last 10 to 15 years cannot continue.

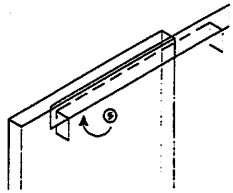
The authors are of the opinion that to assist with the drying of wall components, exterior walls must incorporate a drainage cavity (drain screen system) to allow drainage of water that penetrates the stucco.



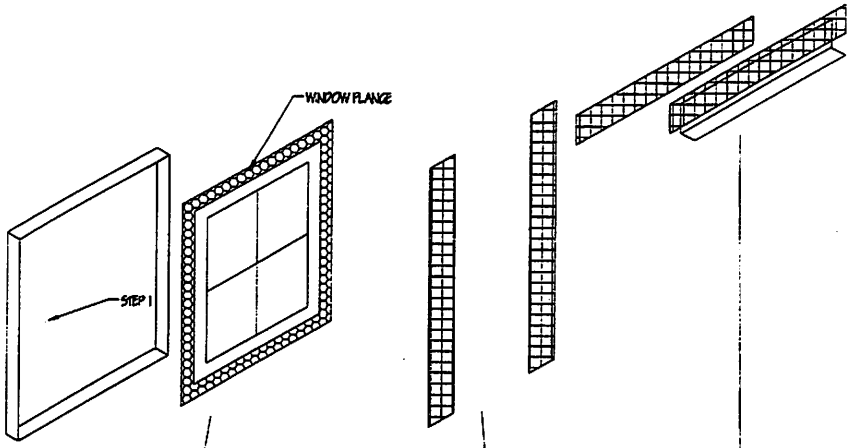
APPLY BOTTOM STRIP OF PEEL AND STICK MEMBRANE INTO ROUGH OPENING.
INSERT BOTTOM GUSSETS INTO PLACE

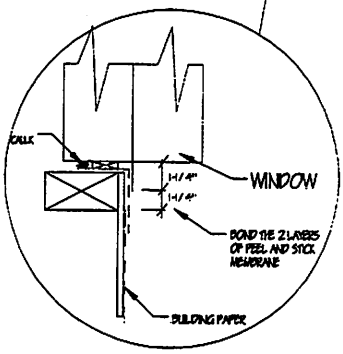


APPLY SIDE STRIPS OF PEEL AND STICK MEMBRANE INTO THE WINDOW ROUGH OPENING.
INSERT TOP GUSSETS INTO PLACE

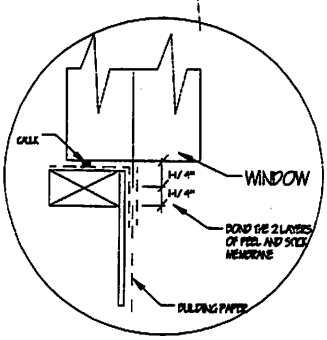


APPLY TOP STRIP OF PEEL AND STICK MEMBRANE

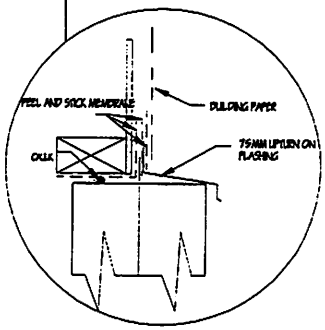




WINDOW SILL DETAIL



WINDOW JAMB DETAIL



WINDOW HEAD DETAIL

FIGURE 1

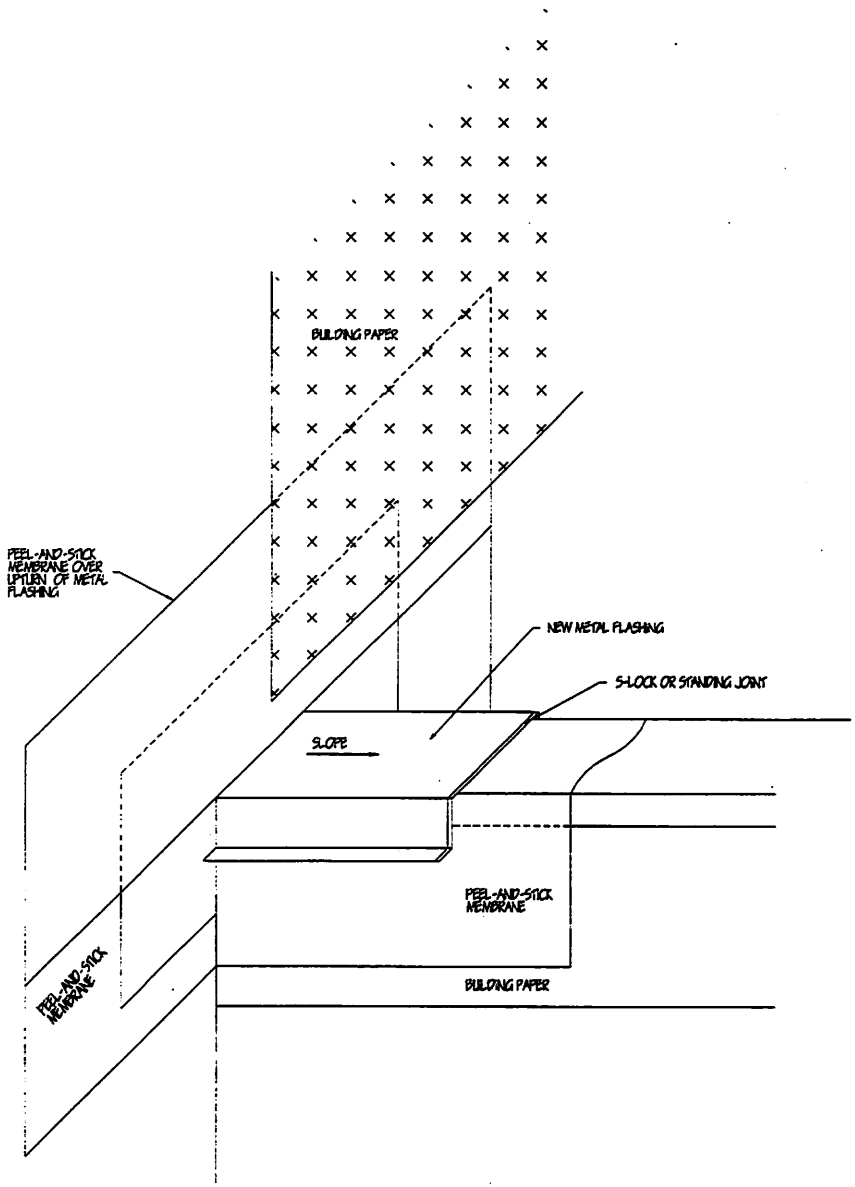

BUILDING PAPER
PEEL-AND-STICK MEMBRANE OVER UPTURN OF METAL FLASHING
NEW METAL FLASHING
S-LOCK OR STANDING JOINT
SLOPE
PEEL-AND-STICK MEMBRANE
PEEL-AND-STICK MEMBRANE
BUILDING PAPER

FIGURE 2

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Solid Masonry Construction of a High-Rise Residential Building: A Case Study For The Nineties

Mr. James Lischkoff, P.Eng. *

Abstract

The problems of solid masonry construction associated with rain penetration are well documented. Designers and builders have tended to avoid such problems by building cavity masonry walls where the collar joint is left free of mortar, allowing any water that has penetrated the exterior wythe of brick to drain to the exterior via flashings. Consequently, the construction of solid masonry walls is rare today and has been solely regulated to low-rise industrial type of buildings.

One exception has been the design of a nine-storey residential building built in Toronto during 1995. This particular building featured a French neo-classical look, including numerous precast lintels, sills and architectural projections making it difficult to incorporate a free draining cavity. Instead a solid masonry approach was adopted using several innovative features to prevent the ingress of rain into habitable spaces.

The exterior wall comprises of a 100 mm (4 in) clay brick, a 25 mm (1 in) collar joint filled with mortar, a 90 mm (3.5 in) interior wythe of concrete block, 25 mm (1 in) of semi-rigid insulation sheathing (acting as both a drainage layer and air barrier), interior steel studding with batt insulation, and a polyethylene vapour barrier covered with drywall.

Although a number of masonry related water resistant features have been built into the design such as tooled exterior joints, parging of the cold face of the brick and tooling of the interior block joints, the design assumes that when water penetrates through the masonry it is collected by the insulation drainage layer.

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The interior drainage layer is connected to the exterior via flashings and drainage openings (filled with insulation) that are located in the joints between masonry units.

Key Words

solid masonry, brick, cavity, drainage, collar joint, high-rise, residential, building

Solid Masonry Construction of a High-Rise Residential Building A Case Study for the Nineties

Mr. James Lischkoff, P. Eng.

Background

In 1990 a Toronto-based developer teamed up with a local and prominent architectural firm, Page & Steele Architects, to design and build a period looking, nine-storey residential condominium building featuring an 18th century French neo-classical facade. The exterior cladding consisted of salmon-coloured Rosefield brick trimmed with numerous precast lintels, sills and ornamental projections. In order to duplicate as authentically as possible the original design, solid masonry construction was mandated for the exterior walls. This requirement bucked the trend of constructing cavity veneer walls which had become common-place over the last 20 years for high-rise masonry buildings.

A building science engineering firm (Trow Consulting Engineers Ltd.) was contacted to assist in the detailing of the building envelope during the design stage and to oversee the quality control during the construction phase.

Cavity Veneer or Solid Masonry

From the early construction of single wythe masonry walls, it was recognized that it was impossible to prevent rain penetration through the mortar joints of masonry. Water would inevitably find its way to the interior through the myriad of cracks that would develop primarily at the mortar/brick interface. This type of cracking was considered normal, usually not impacting aesthetics or structural considerations. However, sealing such cracks against water penetration (via gravity and capillarity) proved futile.

The next improvement involved the use of two wythes of masonry separated by a collar joint filled with mortar. In theory, increasing the direct path from outside to inside and incorporating a mortar barrier (the filled collar joint) should have adequately prevented water penetration to the

interior. In practice, this was not the case as it was not possible to fill the collar joint completely. Solid masonry construction continued to be plagued with water penetration problems.

Finally, the cavity veneer wall was borne which recognized that, while it was not possible to prevent water from penetrating through the cracks of the masonry cladding, any water that did penetrate could be collected and drained to the outside via the drainage cavity and flashing before it had a chance to find its way to the interior habitable spaces. The inner wythe usually consisted of block masonry or steel studs which was prepared to accept interior finishes. This highly successful approach has been well documented and generally accepted as the preferred method to construct masonry walls. The drainage cavity, being considered as the superior water control feature, also allowed for the inclusion of cavity wall insulation, creating an effective thermal layer essential in today's energy sensitive society. Consequently, solid masonry construction has primarily been relegated to one-storey industrial buildings.

In this particular case, the developer and the French neo-classical design precluded the use of a drainage cavity. However, the design team was not prepared to relinquish the principle of drainage, since it was acknowledged that some water would invariably penetrate through the exterior masonry, and therefore an innovative backup drainage system was designed and built. The final wall design included the following components:

- 100 mm (4 in) salmon coloured Rosefield clay brick
- 25 mm (1 in) mortar filled collar joint
- 90 mm (3.5 in) concrete backup block
- wall ties
- 40 mm (1.5 in) semi-rigid fiberglass insulation with the facing (turned to the warm side)
- 40 mil PVC through-wall flexible flashings
- Insulation facing taped and sealed as the air barrier
- 90 mm (3.5 in) steel studs with fiberglass batt insulation, between studs
- 6 mil polyethylene vapour barrier
- 12.5 mm (0.5 in) gypsum wall board.

Major Issues

Three major issues were defined as requiring special attention and consideration: 1) brick durability, 2) resistance to rain penetration and condensation control, and 3) quality control.

Brick Durability

The exterior brick wythe consisted of 100 mm (4 in) Rosefield modular brick manufactured by Canada Brick. The interior wythe consisted of 90 mm (3.5 in) concrete block.

The lack of a drainage cavity, which under normal circumstances would also facilitate drying, suggested that in this case the exterior brick would remain wetted for longer period of times and therefore would have to be sufficiently resistant to freezing and thawing damage. In order to ensure optimum durability, the following material parameters were measured.

The Exterior Brick Wythe

- compressive strength
- 24-hour cold water absorption
- 5-hour boiling water absorption
- saturation coefficient
- resistance to freezing and thawing
- porosity
- efflorescence
- brick prism efflorescence

The Interior Block Wythe

- compressive strength
- 24-hour water absorption
- dimensions
- density
- net area
- drying shrinkage

The Mortar

- compressive strength
- efflorescence
- water soluble chloride ions
- fine aggregate gradation
- air content

Resistance to Rain Penetration and Condensation Control: Design Considerations

In order to minimize the amount of water entry through the exterior brick wythe via gravity or capillarity, the mortar joints were concave-tooled, improving the mortar to brick bond, creating a dense mortar face, and eliminating horizontal surfaces on which water could collect. In addition, all precast sills and horizontal projections were sloped outwards.

Care was taken to completely fill the collar joint with mortar and the mortar joints on the warm side of the concrete backup block were also tooled. All cracks visible in the mortar joints of the block backup were filled prior to installing the wall insulation.

Semi-rigid fiberglass sheets of insulation 40 mm (1.5 in) thick were fastened directly to the block backup with fastening pins. The insulation was installed so that the spun-bonded polyolefin facing was turned towards the interior. The facing joints were taped and the edges of insulation sheathing were sealed to the ceiling, floor and wall concrete components using polyurethane foam. In this manner, the insulation facing provided the air barrier continuity. (The electrical wiring was located within the steel stud space negating penetrations through the air barrier facing.) The bottoms of the insulation sheets were tucked into continuous through-wall flashings which extended to the outside front edge of the exterior wythe of brick. The spun bonded polyolefin facing, although air tight, is vapour permeable, and any moisture from the interior spaces that condenses on the facing will eventually find its way (under a temperature and vapour pressure gradient) to the warm side of the block backup where it will re-condense. If sufficient accumulation occurs, then the condensed moisture can flow down to the through-wall flashings that will eventually drain it to the exterior.

The through-wall flashing materials were made from 40 mil thick PVC flexible membranes with enhanced tear resistance and cold weather flexibility properties. The flashing joints were sealed using a cold compatible adhesive.

Although no drainage cavity was included, drainage openings in both the brick wythe and concrete block backup were provided and filled with semi-rigid fiberglass insulation. The drainage openings were placed in the vertical mortar joints in both the brick and block wythes and offset from one another so that the drainage openings in the brick did not line up with the drainage openings in the block.

Although the design made every effort to minimize the entry of water from the exterior and condensation from the interior into the wall system, a backup drainage system incorporating semi-rigid sheets of fiberglass insulation, through-wall flashings and drainage openings was also installed to collect and drain outwards any moisture that might penetrate the wall components.

Quality Control

In addition to confirming the suitability of material properties and providing a "belt and suspenders" type of design, workmanship was carefully monitored during the construction process. Erection of the exterior brick was done from the outside using scaffolding while the concrete block backup was laid from the interior off the floor slabs. The erection of the brick and block backup was staggered in order that the inside face of the brick could be parged with a thick coating of mortar. This allowed the concrete block backup units to be tightly placed against the mortar parging minimizing voids in the collar joint. All joints between brick masonry and other building components on the exterior, such as precast elements, were caulked using a two-stage jointing system and were carefully integrated and coordinated with the construction of the walls. Full time on-site inspection of all wall components was provided.

The cost to construct this particular solid masonry wall was virtually the same as a cavity veneer wall. There was some cost savings in material as the solid masonry wall required a thinner block backup wythe. The labour costs were identical. Scaffolding costs were not considered, as installing the brick from the exterior was not a prerequisite for solid masonry construction. Scaffolding was used for other reasons

Summary

The building was completed in 1995 and received an Excellence of Design award from the City of North York. The risk, with respect to water penetration, was eliminated through the use of an innovative insulation drainage layer which did not measurably add to the cost of construction and provided for a "belt and suspenders" approach to controlling water penetration. After one year of occupancy, there have been no reported incidences of water penetration through the exterior walls.

Another Look at Internally-Insulated Basement Walls

J.Timusk[1] and K.D. Pressnail[2]

Abstract

Cold climate building practice has traditionally focused on heat and moisture flow from the heated interior space. Hence, the familiar one third/two thirds rule about the location of vapour retarders in insulated walls and the one to ten rule which suggests relative vapour permeance of the vapour retarder and the outer-most wall-forming layer. These rules of practice are predicated on the heating season governing the building envelope design.

However, we are now finding that all of the seasons have an impact on the performance of the thermal envelope, and therefore must be considered. This includes the impact of seasonal variations on the below-grade portion of basement walls. While the above-ground portion of a building sees the same climate which consists of all of the seasonal variations, each soil horizon experiences its own climate. On one hand, the below-grade climate can be blamed for the largest proportion of the call-backs; yet the below-grade climate offers interesting possibilities for the control of moisture in basement walls and the indoor air. In this paper, it will be shown that moisture problems associated with internally-insulated basements can be eliminated by omitting the dampproof layers and the vapour retarding surfaces from the lower portion of the basement wall, while providing for the removal of water which has leaked through the basement wall or condensed on its interior surface. The proposed approach takes advantage of the relatively stable soil temperature and pore water vapour pressure adjacent to the lower portion of the basement wall. The above-grade and the first 600mm below-grade portion of the wall are built in the traditional manner. However, the reader must be cautioned that this proposed approach has not yet been field tested. Further, the design illustrated in this paper is contrary to present code requirements.

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Another Look at Internally-Insulated Basement Walls

J. Timusk and K.D. Pressnail

Introduction

The basement wall and the built up roof share many problems. Both of these assemblies provide a separation between indoor and outdoor climates, and part of the time, water may enter both of these assemblies including the thermal insulation. "Part of the time" can range from a few hours to the life of the building. To exclude rain and melt water from the roof construction, a roof is provided with an adequate slope to drain away surface water and attempts are made to make the roof membrane completely water tight. Success is contingent on the roof membrane remaining perfect.

Similarly, basement backfill materials or special draining layers are provided so that hydrostatic pressure against the basement wall and the inevitable leakage through cracks is avoided. Dampproofing is then applied to the surface of the wall in contact with soil to control wetting due to water vapour diffusion or capillary suction.

The entry of room-side water vapour into roof or wall insulation is controlled by providing an air barrier and a vapour retarder. Unfortunately, in practice, both have proven to be unreliable. Once water has entered the space between the outer and inner moisture-excluding layers, it becomes trapped. This can lead to many problems including: decay of wood members, corrosion, freeze-thaw damage, and the loss of thermal resistance of insulating layers. Further, it has been clearly established (CMHC) that dampness in basement walls can lead to mould and mildew growth, which in turn, leads to adverse health consequences.

Solutions which eliminate trapped-water have been developed for both roofs and basement walls. Such solutions include the protected membrane roof and the externally insulated basement wall. In both of these cases, the outer membrane has been eliminated, allowing the insulation to dry to the outside air or to the soil [1]. Needless to say, when materials are placed in an extreme environment, which includes contact with liquid water and temperature extremes of 100K, they must be capable of withstanding such exposure.

In the case of the internally-insulated basement, solutions are needed now to the problems of trapped water. Unlike the built-up roof, the internally-insulated basement wall is exposed to a much more stable climate. Thus, problems of trapped water may be easier to solve. Before solving these problems, it is helpful to examine the soil climate.

The Soil Thermal and Moisture Regime

Except for the layers close to the ground surface, the relative humidity in the soil remains close to one hundred percent throughout the year. In other words, for a given soil temperature, the water vapour pressure is close to the saturation value. The air in the soil pores is nearly saturated, and much of the soil is within capillary reach of the ground water table. Capillarity is an important soil property, particularly when frost-heave and adhesion freezing are a concern.

When soil temperatures are examined, there are several factors that influence the thermal regime. The thermal mass of the soil, ground cover, shading, as well as the latent heat exchange associated with freezing, thawing, evapouration and condensation all play a significant role in establishing the local soil climate. As shown in Figure 1 [2], the mean annual soil temperature for a particular location and ground cover does not vary noticeably with depth and is usually 2K to 6K above the mean annual air temperature due to geothermal heat. In contrast, the amplitude of the soil temperatures over a year varies, and diminishes rapidly with depth. In addition to the increase in thermal stability with depth, a time lag sets in. At a depth of 3m, the soil temperature lags six months behind the ground surface temperature. Thus, the July heat wave reaches the basement floor in January. This lag, and the increasing thermal stability with depth, may be used to advantage when designing internally-insulated basement walls.

The vertical line shown in Figure 1 represents in the indoor basement air temperature. With the exception of the months of June, July and August, this figure shows that the soil surrounding an Ottawa basement represents a heat sink throughout the year. In fact, only the top few hundred millimeters of soil ever becomes a heat source, and only for a short period during the summer.

The lion's share of the temperature transition from the inside temperature to the soil temperature takes place through the thermal insulation in the wall. The soil thermal and moisture regime can be considered to be a series of micro-climates which are a function of the depth below the ground surface. As a result , heat, air and water vapour transfer will occur between these various climate zones. Such flows will be two-dimensional and will necessarily lead to flow control elements which may be either vertical or horizontal.

In contrast, the above-grade climate, which lacks the stabilizing mass of soil on one hand and is affected by diurnally and seasonally variable solar radiation affects on the other, experiences large and rapid temperature changes. In the case of built-up roofs, it is the large diurnal variations which can dominate performance; fortunately, for walls and, particularly basement walls, it is the

seasonal temperature fluctuations and the associated water vapour pressure variations that are the primary concern. Of course, there are always exceptions. Outer wall elements must endure diurnal solar variations, and the related problems of sun-driven moisture.

Successful wall designs must moderate the environment, by controlling the flow of heat, air flow, and the movement of water as vapour and as liquid [3]. Temperature and water vapour interactions can best be illustrated by examining a psychrometric chart as shown in Figure 2.

The Psychrometric Chart

This chart outlines graphically the relationships between temperature and the properties of air/water vapour mixtures. The amount of vapour an air mass can hold depends on temperature; hence, the dew point or one hundred percent relative humidity line in the chart provides a practical boundary for all possible air/water vapour mixtures. However, supersaturated air can take us to the left of the boundary.

This chart shows that as the temperature of the air increases, the capacity of the air to hold moisture also increases. The vertical scale of the chart depicts the water vapour content of air in kilograms of water vapour per kilogram of dry air. It can also be stated in terms of water vapour pressure, the "force" which "drives" water vapour diffusion.

During cooling, the moisture content of the air remains unchanged, as described by the horizontal lines on the psychrometric chart. In the process, relative humidity lines are crossed, indicating a progressive increase in the relative humidity, until the 100% relative humidity or the dew point line is reached. At this point, the air can not hold any more water, and on further cooling, moisture in the air starts to condense. This process is described graphically by moving along the downward-sloping dew point line. In the process, water condenses from the air, and if the condensing surface is not sufficiently permeable, beads of water will form on it. This water will eventually drain downward if the condensing surface is vertical. Hence, the appearance of water on the basement floor may be due to either the leakage of water through the wall or condensed water from the interior.

Seasonal effects of the outdoor climate can be illustrated on the psychrometric chart as well. The two shaded areas on the psychrometric chart indicate zones of high and low moisture content, which correspond to summer and winter conditions respectively. During the summer the outdoor vapour pressure is rather high, while during the winter, the vapour pressure is relatively low. Between these two zones is a region along the dew point line that represents the soil conditions

adjacent to the basement wall and floor, at least 600mm below grade. This region follows the 100% relative humidity line since, at all times, the air in soil pores is close to saturation.

To get from basement air to the soil we have to move through the thermal insulation. Since the soil below the top few hundred millimeters is always a heat sink as shown in Figure 2, this movement is always to the left. Therefore, the outer layers of the insulation are, at all times, close to the one hundred percent relative humidity line. The region between the one hundred percent and the eighty percent relative humidity lines represents a region where many organic materials and metals are prone to decay. This "danger zone" must be recognized since it can lead to serious deterioration and indoor air quality problems if it is not considered in the design process.

Design Implications for Internally-Insulated Basements

Having recognized the "danger zone", a few observations about the design of internally-insulated basements can be made:

1. Once the depth below grade is more than a few hundred millimeters, water vapour diffusion membranes are not required. In the interests of the indoor climate, low permeance membranes are best avoided. This includes polyethylene sheets under the concrete floor, as well as low permeance floor coverings.
2. Materials which can degrade in a moist environment must be kept out of the danger zone, or the eighty percent to one hundred percent relative humidity zone.
3. Bulk water leakage, air leakage, and soil gas entry must still be managed.

So why are no vapour diffusion control membranes required? In the case of the internally-insulated basement, if condensation does take place, it will occur on the first solid surface encountered. This surface is usually the concrete wall. So long as the surface has not been treated, the water may be absorbed by the concrete. Any water that isn't absorbed, will run down along the wall surface. This movement of water is completely harmless so long as a suitable drainage channel is provided between the basement wall and the basement floor slab. The small quantities of water involved here would be absorbed by the crushed stone layer and the soil below the basement floor slab.

Without vapour diffusion control membranes, the basement wall can act as a passive dehumidifier during the summer. Such an approach, offers a significant energy advantage over conventional heat-pump dehumidifiers. Heat pumps consume electricity. The heat released includes the electricity consumed as well as the heat of vapourization. This heat is dumped into the basement at a time when cooling is often required. However, if the basement is passively dehumidified, then

two savings occur. First, no electricity will be consumed. Second, the release of the latent heat will occur on the outboard side of the thermal insulation. Thus, most of the latent heat will be transferred through the concrete wall to the soil. Further, passive dehumidification will not only lessen the cooling load, but it is truly a passive system. There are no moving parts!

During the winter, the diffusion process is reversed. The vapour pressure gradient attempts to move water from the soil into the basement. At such times, a wall that has no vapour diffusion control membranes can act as a passive humidifier. This passive humidification occurs at a time when most adequately ventilated houses experience a moisture deficiency.

Passive dehumidification and humidification can also be provided by the floor. However, the above-grade and immediately below-grade portions of the wall must be treated in the traditional manner. During the winter, these areas are just too cold. This would lead to dehumidification at a time when humidification is required. Portions of the wall that are not sheltered by the soil must be kept dry. Further, the vertical transfer of moisture from the lower portions of the wall during cold weather should also be avoided.

When vapour diffusion control membranes are omitted, moisture sensitive materials may be degraded. In order to avoid degradation of moisture sensitive materials, materials such as wood should be removed from the danger zone. The wall studs and the bottom plates can be isolated from the concrete wall and floor slab by facing the studs and plates with materials such as polystyrene insulation. The entire wall could be insulated with expanded or extruded polystyrene insulation. However, if this type of insulation was used then the wall would no longer act as a passive humidifier or dehumidifier.

To control the leakage of bulk water, air leakage, and soil gas entry, traditional measures are still required. The selection of perimeter materials and details where the first line of defense is to drain water away from the house are strongly recommended. Measures such as the use of draining boards to minimize leakage due to hydrostatic pressure still ought to be taken [4]. However, if minor leaks occur through the basement wall, then this water can be accommodated by the provision of a drainage space between the floor slab and the basement wall.

To control air leakage and soil gas entry, an air barrier must still be provided. The interior gypsum board can be used as an air barrier. Since the drainage passage between the floor slab and the wall represents a potential pathway for the entry of radon gas, it is important that a continuous air barrier be provided.

Proposed Design

With these necessary design elements in mind, we can now turn to Figure 3. This figure depicts an internally insulated basement wall that has been insulated using glass fibre batt insulation. This proposed wall section provides passive humidification and dehumidification while protecting moisture sensitive materials in the wall. Further, this wall section controls: the leakage of bulk water, the movement of air through the wall, and soil gas entry.

The basement wall can be divided into two parts: the upper part and the lower part. The upper part extends from the underside of the first-floor subfloor to 600mm below the ground surface. The lower part extends from 600mm below grade to the basement floor slab. Six hundred millimeters is a convenient break point since previous building codes required insulation to this depth.

The upper part of the wall should be designed in the traditional manner. The exterior concrete wall surface should be dampproofed and the interior wall surface should be covered with a sheet of polyethylene. The face of the stud that lies against the concrete should be covered with a 35mm thick layer of polystyrene foam. These "thermal studs" should be continued to the bottom plate. The stud cavity should be blocked at 600mm below grade in order to provide a separation between the upper and lower portions of the wall. The stud cavity should be filled with glass fibre batt insulation and a polyethylene vapour retarder should be extended from the subfloor to the blocking. The assembly is covered with gypsum board which is sealed to form the air barrier. The gypsum board is continuous over the wall height, and should be terminated approximately 10mm above the concrete floor slab. This latter detail is necessary in order to avoid wicking of water into the gypsum in the unlikely event of flooding.

The lower part of the wall, as shown in Figure 4, is similar to the upper part except no dampproof coatings are applied to the exterior of the wall, and no polyethylene vapour retarders are placed on the interior. The bottom plate, like the thermal studs, is also faced with a 35 mm layer of polystyrene foam. While the use of polystyrene keeps the vulnerable wood away from the cool, damp concrete surfaces, the studs may be simply offset from the wall by 35mm. Unfortunately, this results in a "springy" wall if the frame is only attached at the top and bottom plates. However, the use of the foam as a "thermal break" is strongly recommended for the bottom plate.

At the base of the wall, a trough or space between the floor slab and the wall must be provided. This vertical separation can be easily created by casting strip of glass fibre insulating board into place. This drain should lead to a sand layer between the toe of the footing and the floor slab. This layer can be created by placing a bed of clean sand on the edge of the footing before the slab is

cast. This cushion represents good building practice since it prevents bonding between the slab and the footing. The slab can now shrink without restraint, and therefore, the slab is less likely to crack.

Continuity of the air barrier is ensured at the concrete floor slab by compressing a layer of polystyrene between the slab and the bottom plate. Acoustical sealant place between the bottom plate and the gypsum drywall continues the air barrier. At the top of the wall, the air barrier can be continued by sealing the spun-bonded polyolephin header wrap to the gypsum board with acoustical sealant. The entire wall frame can be assembled on the basement floor and tilted up into position. To ensure a good air and water seal at the floor slab level, the polystyrene along the bottom plate can be compressed by driving the wall downward with wedges along the top plate.

Conclusion

The omission of vapour retarding membranes and dampproofing on the lower parts of below-grade walls and floors logically follows from an examination of the soil moisture and thermal regime surrounding basements. Given that some basements will inevitably be internally insulated, it is incumbent upon designers to develop designs that perform well. The design proposed here represents sound building science practice. Perhaps it is time that the practice of designing and building below-grade walls reflects the inherent advantages of a soil-sheltered environment.

Finally, the concepts outlined in this paper for internally insulated basements in cold climates, can be applied to basements in mixed climates. These concepts can also be applied to externally-insulated basements. When external basement insulation is used, the concrete wall is, accordingly, warmer and drier. However, favourable moisture and thermal gradients can still be used for passive humidification and dehumidification.

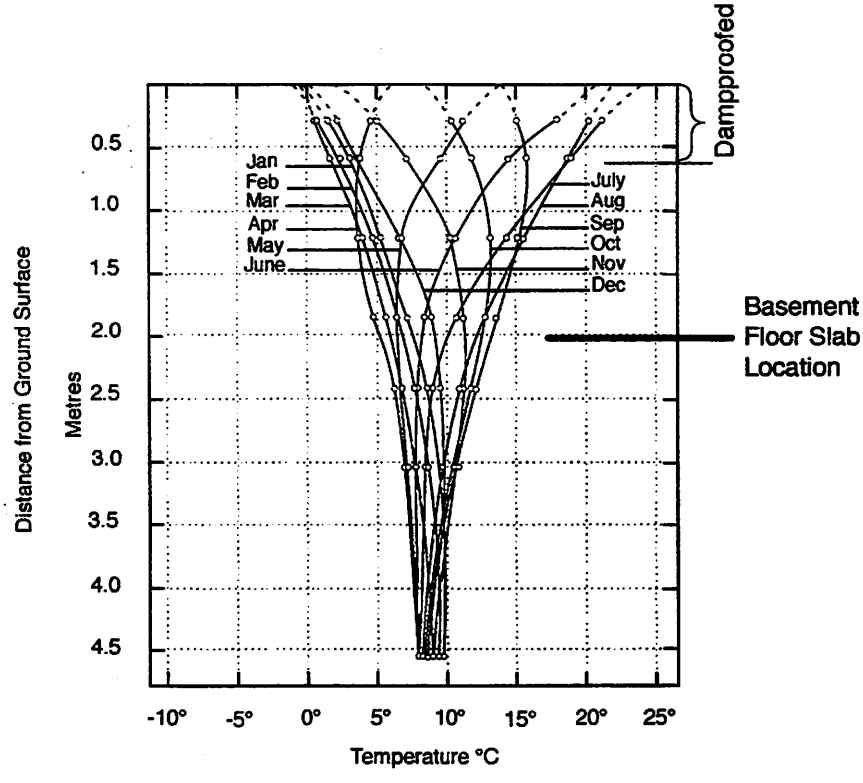

Figure 1 Shows seasonal variation of soil temperature with distance from ground surface

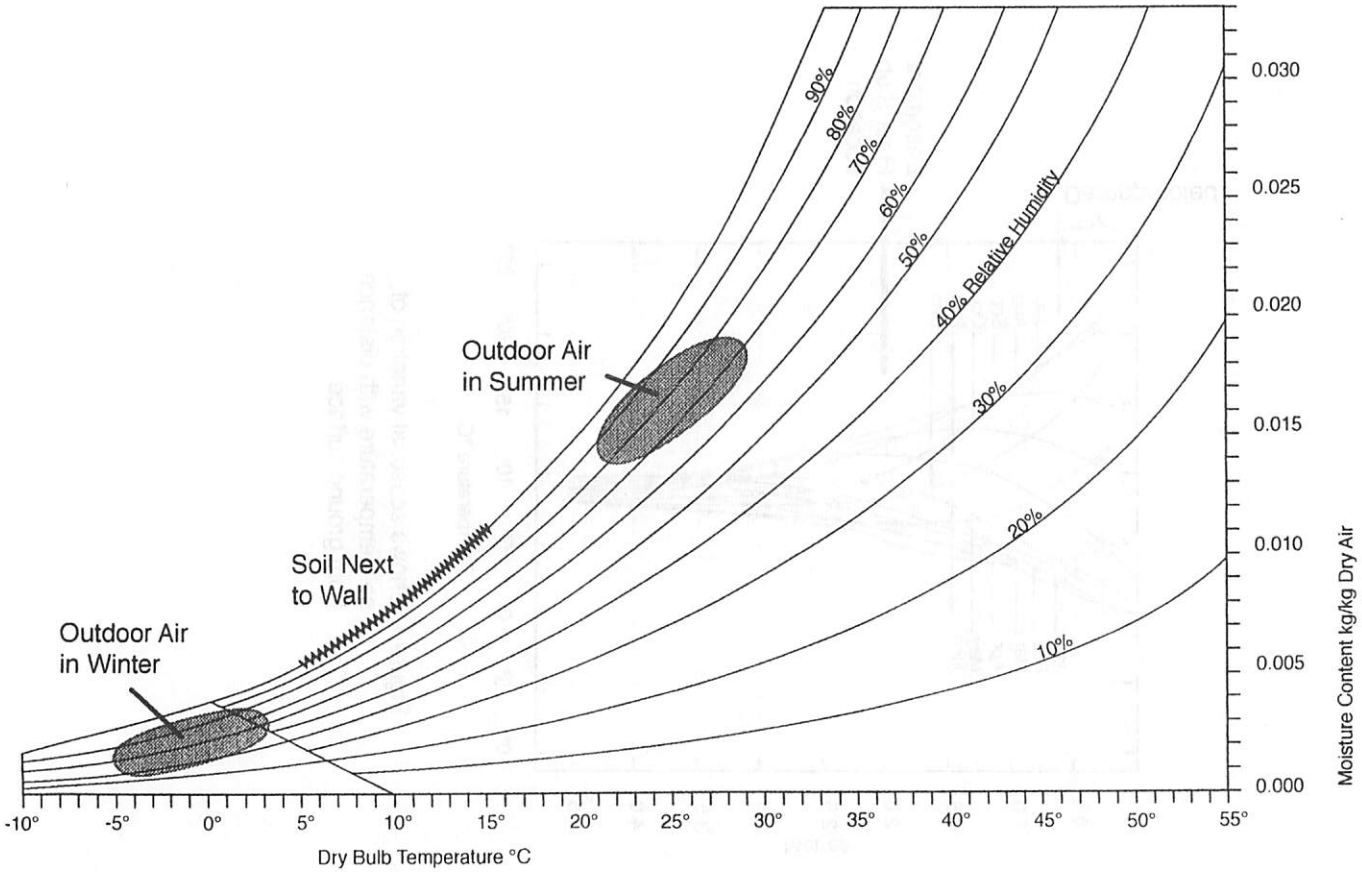

Figure 2 Psychrometric Chart denoting conditions of outdoor air, summer and winter, as well as the soil next to the basement wall from the footing height to 600 mm below grade

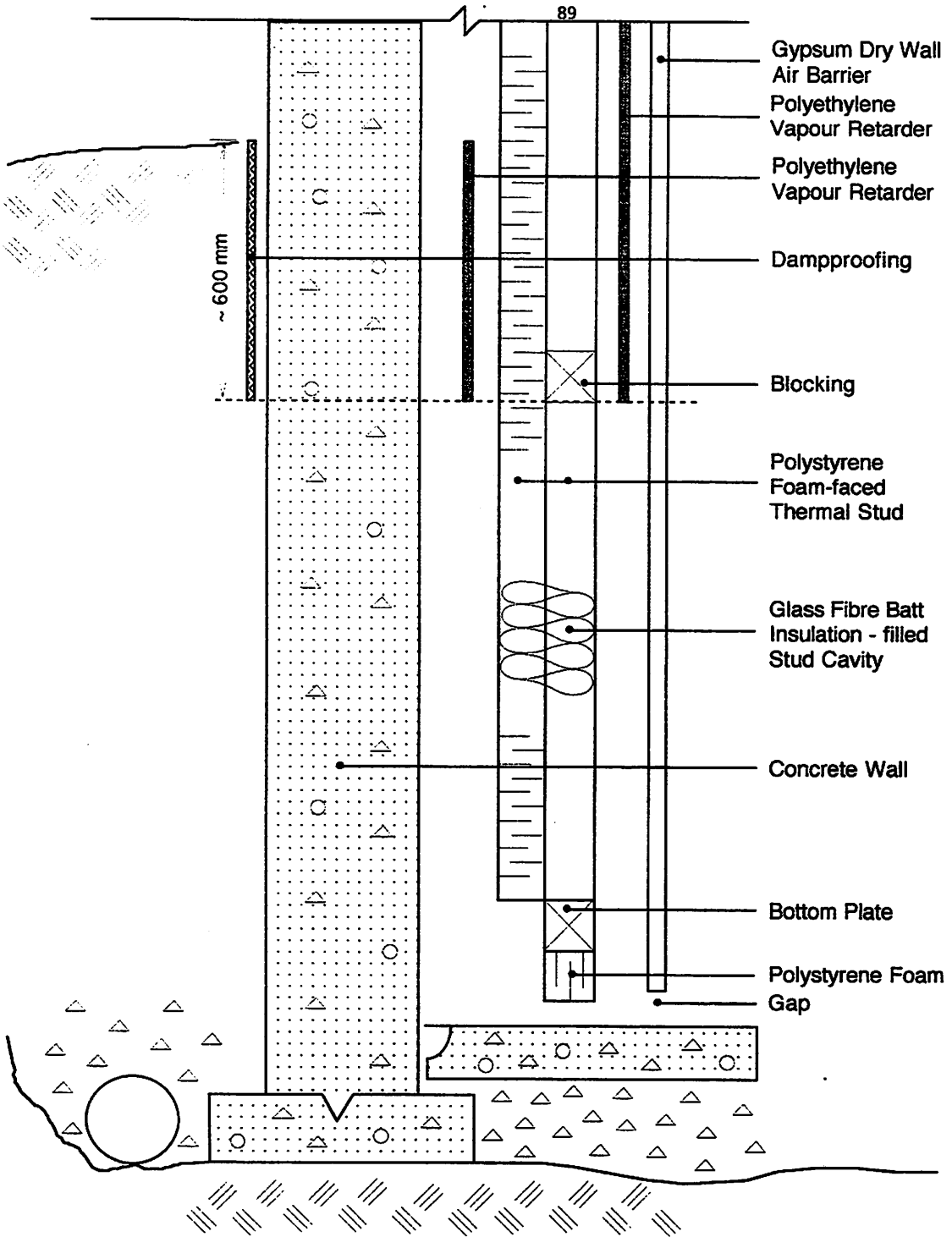

Figure 3 Expanded section through the internally insulated wall

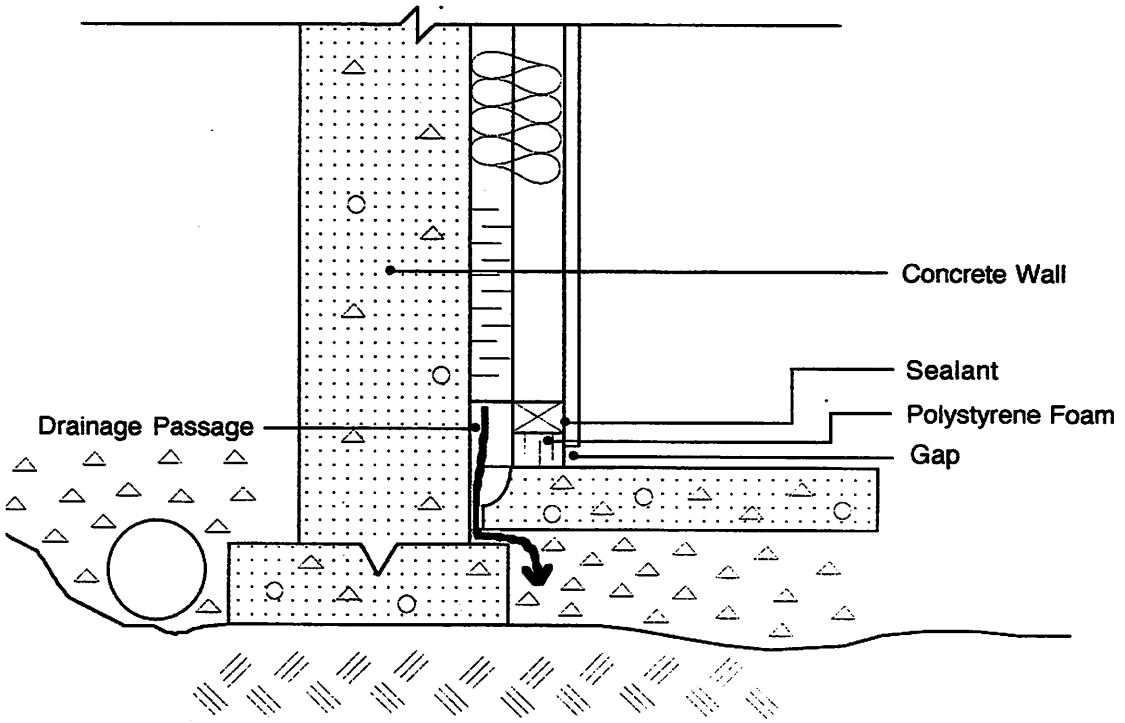

Figure 4 Drainage passage formed between the basement floor slab and wall-to-footing

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Moisture Engineering

Achilles N. Karagiozis[1]

Abstract

The service life of a building envelope system depends in part on the integrated design approach employed during conception. Integrated design approaches must take into consideration material behavior, system and sub-system characteristics, environment, workmanship quality, buildability and design analysis. Criteria for the performance of systems are the long-term hygrothermal and structural performance of the whole construction entity. Hygrothermal performance of a building envelope system is dictated by the response of the system to combined heat , air and moisture transport excitations produced by exterior or interior forces. This paper deals with hygrothermal performance in term of the approaches available in moisture engineering. Moisture engineering analysis of the hygrothermal performance of building envelope systems can be carried out by three distinct methodologies, laboratory testing, field monitoring and computer modeling. These methodologies will be discussed here, but emphasis will be given to modeling .

At the end of the recent IEA Annex 24 a total of 37 hygrothermal models were reported in Task 1 on Modeling. These models vary with respect to the extent of treatment of dimensionality (1-D,2-D and 3-D), exactness of the porous media physics (vapor flow, liquid flow, air flow, freezing, condensation, evaporation), material transport properties (constant, simplified or full distribution) and environmental conditions (relative humidity, temperature, solar radiation and precipitation). Classification of the models have lead to two distinct classes of models, those that are simplified models and those that are advanced full models. Only advanced models can be employed in the analysis and generation of design guidelines of the long-term hygrothermal performance of building envelopes. Indeed, moisture engineering has been "born" with the recent development of a few advanced hygrothermal models. The most advanced of these models is LATENITE developed at NRCC.

In this paper, information regarding the LATENITE model will be presented. The assumptions and limitations of hygrothermal modeling with respect to moisture engineering will be discussed in detail. The importance of including the appropriate input parameters in each moisture engineering analysis will be addressed. An example case of a masonry wall system will be presented to show the effect of wind-driven rain on both the thermal and moisture behavior of a building envelope wall system.

KEY WORDS: moisture engineering, hygrothermal analysis, modelling, masonry

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Moisture Engineering

Achilles Karagiozis

Introduction

Moisture engineering deals with the characterization of the complex heat, air and moisture transport behavior of building envelope systems. The service life of a building is strongly correlated with how the individual systems of building envelope components (walls, roofs and basements) manage their reponses to heat, air and moisture transport excitations. Moisture accumulation in building systems can cause deterioration in various forms, i.e., surface damage, discolourization by efflorescence, aging processes, chemical damages, moisture induced salt migration, structural cracking due to thermal and moisture gradients, corrosion of steel, and mould or bacteria growth. Damage to buildings caused by moisture induced problems annually amounts to several billion dollars in North America alone.

Over the last 30 years, moisture engineering relied heavily on experimental approaches to resolve moisture performances of building envelopes. Hundreds of examples of research investigations, employing laboratory and field monitoring, Hens [1], have been performed in both North America and Europe on specific building envelope case studies. A disproportionate number of these have only concentrated on the thermal performance characterization of building systems. However, the majority of our current design guidelines have essentially been generated by past experimental analysis. This has provided invaluable results in some case, but in others more questions than answers. During the same period, 1960-1990, moisture modeling of building envelope systems was not developed to the same level of expertise as that provided by experimental approaches.

In the 90's, both experimental and modeling methodologies used in moisture engineering analysis have been enhanced considerably. Indeed recently, modeling capabilities have been employed jointly with experimental analysis to provide unique

turn key solutions to challenging building envelope problems [2], [3] and [4]. Currently some of the state-of-the-art hygrothermal models that can integrate system and sub-system performances of specific building envelopes system and can provide nearly quantitative answers that can not be generated by the experimental approaches. The major impediment in the experimental approaches is the lack of a reliable /accurate measurement probe for the in-situ measurement of moisture content.

Sophisticated hygrothermal models have not yet been available to building envelope designers, as they are mainly research models. As the shift of regulatory design code (NBCC) approaches from the limited prescriptive design to performance and objective based building envelope code is being adopted, the demand for design assessment and performance models will increase many-fold. Scaled down versions of these sophisticated moisture modeling tools will eventually be distributed to building envelope designers. The main advantage of modeling is that, if the building envelope system has been carefully characterized, modeling can predict the long-term hygrothermal performance of the system under different climatic conditions, assess the effect of changes in the interior conditions (HVAC), and the effect of various energy retrofit to the building durability. Moisture load tolerances of various envelope designs can also be investigated with respect to the drying potential and the total system effect of various design alternatives, by employing modeling. Modeling, however, is not meant to replace valuable laboratory and field investigations but to complement them, and extend the information they may provide. In many experimental evaluations of complex envelope systems, simulations can be performed to design, further explain and interpret the experimental results.

The ultimate goal of any moisture engineering analysis is to generate design guidelines. This is where the main advantage in terms of both time and expense lies when employing modeling, but at the same time full understanding of the system is required and only experimental approaches can provide this input. Marrying experiments and modeling allows researchers to generate effective hygrothermal performance guidelines.

In this paper, the essential ingredients required by modeling, for investigating the hygrothermal performance of building envelope systems will be discussed. The input parameters required by sophisticated hygrothermal models will be presented. The state of the art hygrothermal model LATENITE developed by the author [5] at NRC will also be presented. As an example of moisture modeling, the hygrothermal performance of a solid brick masonry wall system will investigated.

Hygrothermal Modeling

In a paper dated in 1953, Hutcheon (Previous Director at NRC (Division of Building Research)), [6] laid out the fundamental considerations in the design of exterior walls for buildings. These over the past 40 years have gained international recognition and have been the basis of what was then named "building science". The critical parameters that define the role of building envelope are still valid today and are:

1. Strength and rigidity
2. Control of heat flow
3. Control of air flow
4. Control of water vapour flow
5. Control of liquid water movement
6. Stability and durability of materials
7. Fire
8. Aesthetic considerations
9. Cost.

Moisture engineering deals with items 2, 3, 4, 5 6 and 9, and the importance to the design and retrofit of systems cannot be underestimated. Figure 1 shows the intricate relationship between the building system and the three environments; the indoor environment, the microclimate adjacent to the building and the macro-climate far away from the building entity. In particular moisture engineering develops the criteria to assess the fundamental considerations presented by Hutcheon (1954) in a quantifiable manner. In this manner a sub-field of building science has evolved to the next level, that of moisture engineering. Hygrothermal performance modelling provides a valuable tool to assess the complex inter-relations of the phenomena involved in the combined heat air and moisture transport processes.

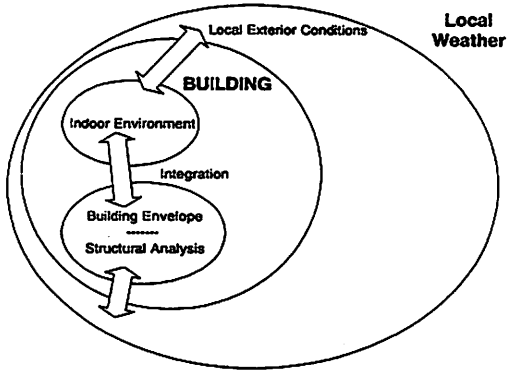

Figure 1: Functional Relationship between Envelope and Surrounding

Requirements for Moisture Modelling

In Figure 2, the four essential ingredients required for hygrothermal performance modelling are displayed. By definition, a computer model is a logical-mathematical representation of a concept or system programmed for solution on an electronic computer. A model is essentially as useful as the level of sophistication embedded into the model. In moisture engineering modelling the most important physics (vapour and liquid flow, forced and natural convection flows, gravity) should be included, full functional dependencies of the heat and moisture transport properties of materials should be accounted for, all important boundary conditions for heat, air and moisture transport should be incorporated, the computational domain must represent as closely as possible the real domain, and the numerical methods must accurately predict mass, energy, and momentum conservation at all times. The results obtained by a simulation depend on the level of accuracy and details provided by the four ingredients of the model.

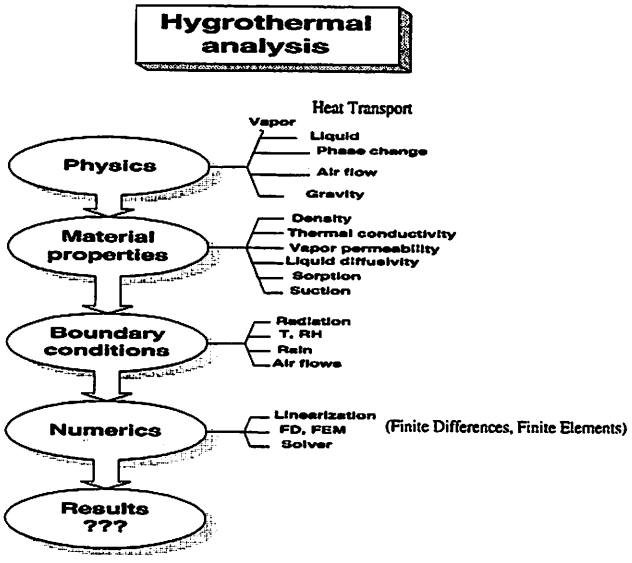

Figure 2: Hygrothermal Permeance Analysis

Until recently, lengthy and expensive experimental studies were usually necessary to clarify what moisture forces various building envelope systems can withstand and what preventative measures were needed. However, today, by employing suitable modeling methods, experimental investigations are reduced in extent, and in some cases they could be eliminated or considerably accelerated. A realistic assessment of the building envelope can be achieved by modeling the combined heat-air and moisture transport on a hypothetical numerical domain which may be supplemented with experimentally determined system and sub-system performances. A building envelope system consists of all 1-D, 2-D and 3-D components such as the material layer systems, and includes all unintentional cracks and intentional openings. Sub-systems are defined by the close formation-interaction of two material systems such as the brick-mortar masonry interface, gluing two material together forming a substrate (EIFS board) and the various waterproofing membranes and coatings. At all times these modeling activities must be fully coupled with representative material properties. The recent International Energy Agency (IEA) Annex 24 on Heat-Air and Moisture Transfer in Insulated Envelope Parts

identified a total of 37 hygrothermal models (Hens et al) of varying degree of complexity. These hygrothermal models can be grouped into two categories; those with entry level idealized performance analysis (design tools) and those with real performance specification analysis capability (regulatory tools). Presently approximately 34 of 37 models belong to idealized performance tools with only 3 (2 of which are developed in Canada, TCCC2D/IRC-VTT and LATENITE/IRC) fit for real performance analysis tools. Essentially these more sophisticated tools can handle all the important transport physics, and become particularly important for developing prescriptive, performance based codes such as NBCC 1995 and objective based codes (NBCC, 2001).

Hygrothermal Model Features

Models range from simplistic to very sophisticated analysis tools, depending on the incorporated features. Depending on the specific features of a hygrothermal model different analysis capabilities exist. Only a few hygrothermal models can assess and realistically predict the short-term and long-term performances of building systems. In particular these advanced models can provide very useful information regarding the drying potential of different wall systems, the vapor control requirements of a particular climate, the energy implications of increased thermal conductivity due to the presence of moisture and phase change effects in porous building materials, the effect of various retrofit options on building envelope performances, and the behavior of innovative materials or products with respect to the whole system. Essentially, the key modeling features required to assess possible moisture damage in building envelopes are:

- Transient heat, air and moisture transport formulation
- 2-dimensional spatial formulation (as a minimum)
- Permitting variable material properties; e.g., as functions of moisture content and temperature
- Accounting for the physics of:
  - -vapour transport
  - -liquid transport
  - -hydraulic transport
  - -moisture capacity of the materials
  - -condensation and evaporation processes

-freezing and thawing processes
-incident solar radiation and sky radiation on exterior surfaces
-rain penetration of exterior surfaces of the building
-air flow through the building envelope

Currently, most models provide deterministic solutions with the exception of LATENITE which also allows randomness in hygrothermal modeling. Randomness is an important feature as the hygrothermal material properties of two samples from the same batch of building materials is never exactly the same. The hierarchy of the capabilities of hygrothermal models from the more basic models to the most sophisticated ones are depicted in Figure 3.

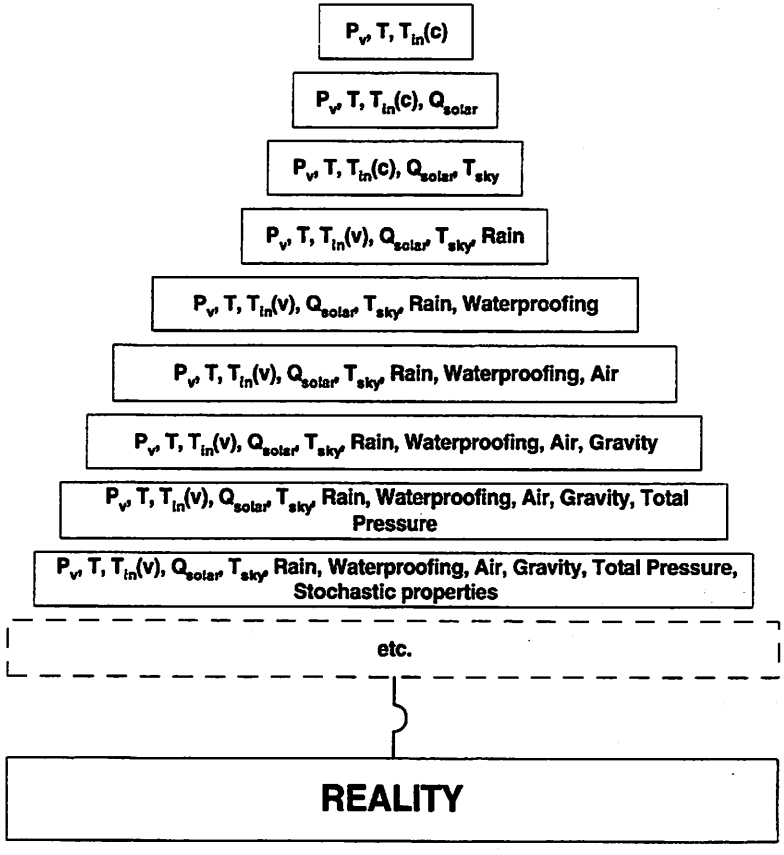

Figure 3: Levels of Sophistication of Hygrothermal Models

Definitions for Figure 3 are: P_v is vapor pressure, T is outdoor temperature, $T_{in}(c)$ constant indoor temperature, $T_{in}(v)$ is variable indoor temperature, T_{sky} is sky temperature, and Q_{solar} is solar radiation,

Boundary Conditions for Hygrothermal Models

The exterior and interior boundary conditions acting on buildings vary with time of day and time of year, making boundary conditions time-dependent (transient). The exterior variations are part of the seasonal and diurnal effects associated with the geographical location of the building. The internal variations are greater due to the time of day and the particular activities undertaken by the inhabitants of the building. Some of the internal moisture sources or sinks depend primarily on the behavior of the inhabitants with respect to preferred interior-climate comfort levels, the number of baths taken, type of cooking, and cleaning, etc. This makes the definition of interior-climate classes complex and dependent on time, location and people's behavior. Additional complexities are introduced since the exterior weather conditions available from airport weather stations must be translated to local site conditions that may be substantially different with regard to hygrothermal loads.

On the exterior of a building, boundary conditions for diffusion and convection processes that should be prescribed for a building envelope wall or roof are:

- Inclination of Structure (Horizontal, Vertical or Inclined)
- Orientation of the Structure (South, North, West or East)
- Exterior air temperature (°C)
- Exterior relative humidity (%)
- Solar radiation (W/m2)
- Aborptivity of exterior surface (-)
- Emissivity of exterior surface (-)
- Convective heat transfer coefficients (W/m^2 °C)
- Mass transfer coefficients (kg/m^2 Pa)
- Water resistant substances (kg/m^2 Pa)
- Rain fall on exterior surface (kg/m^2 hr)

with additional boundary conditions when using the airflow cases:

- Wind speed (m/s)
- Wind Orientation (degrees)

- Stack pressure (Pa)
- Neutral Pressure Height (m)
- Over or Under Pressurization (Pa)

In the more advanced models the heat and mass transfer coefficients are a function of the wind-speed and orientation. The boundary conditions are mainly provided on a hourly basis. Adoption of the 1-hour step was determined by examination of the effect of time-averaging as presented in the section on material properties. This, of course requires an enormous number of boundary conditions that in some cases are not available. Especially in the case of rain fall on the exterior surface of the building, no such information was available. Yet, rain constitutes the most important source of moisture in high-rise walls with capillary-type facades. Today, even within the international research community, moisture-modeling that includes the effect of rain has not been implemented for two main reasons:

- the complexity in the mathematical and numerical procedures to handle rain flow at the exterior boundary surface, and
- the lack of information regarding the amount of rain striking the exterior surfaces of a building.

In LATENITE wind-driven rain has been incorporated by performing a series of 3-D rain droplet simulations and in this way determining the mass flows and wetting patterns of a complete building.

Material Property Characterization

In publications [7] and [8] the direct influence of hygrothermal material properties, water vapor permeability, liquid diffusivity, sorption isotherm and spatial non-uniformities on the overall performance of building envelope systems was investigated. It was generally concluded that material property profile shape must be accurately determined and simplifications to the functional form must not be permitted. The proper characterization of the sorption (including the hygroscopic and capillary regions) and moisture diffusivity transport distribution are the most critical for design considerations. Describing these coefficients with mean constant properties can produce deviations of the order of ±40 % in relative humidity. Deterministic and stochastic applications show smaller differences , ±10 % RH, when deviations of ±40 % of the deterministic properties (vapor permeability and liquid diffusivity) were present.

It is therefore strongly recommended that full functional form of each individual material should be used and simplification of the material properties function is not recommended.

LATENITE 1.2 Hygrothermal Model

Description of Model

The description of the LATENITE version 1.0 hygrothermal model is given by Karagiozis [5], Salonvaara and Karagiozis [9] and Hens [1], and only a brief overview is presented here with regard to the additional features embedded in version 1.2. The moisture transport potentials used in the model are moisture content and vapour pressure; for energy transport, temperature is used. The LATENITE 1.2 model has been recently upgraded to include porous air flow through insulation and cracks by solving a subset of the Navier-Stokes equations, Darcy's equations. The LATENITE model allows treatment of the building envelope system with coupled heat and moisture transport via diffusion and natural and forced convective air transport. Phase changes due to evaporation/condensation and freezing/thawing mechanism are included in the model. In addition the solution domain has been extended to 3-dimensions, allowing real practical problems to be solved. The model recently included the capability for handling internal heat and moisture sources, gravity-driven liquid moisture, and surface drainage capabilities. This model also permits the "capturing" of the various systems and sub-systems anomalies of the building envelope and can be employed in analysis of laboratory experimental hygrothermal results. The moisture transfer equation including liquid and vapour transfer is:

$$m = -\rho_0 D_w(u,T)\nabla u - \delta_p(u,T)\nabla P_v + v_a \rho_v + K(u)\rho_w g$$

where

- m = mass flux, $kg/m^2 \cdot s$
- ρ_0 = dry density of porous material, kg/m^3
- D_w = liquid moisture diffusivity, m^2/s
- u = moisture content, kg_w/kg_d
- T = temperature, °C
- δ_p = vapor permeability, $kg/s \cdot m \cdot Pa$
- P_v = vapor pressure, Pa

v_a = velocity of air, m/s
ρ_v = density of vapor in the air, kg/m^3
K = moisture permeability, s
ρ_w = density of liquid water, kg/m^3
g = acceleration due to gravity, m/s^2.

Moisture Engineering Application: ENGLISH BOND WALL SYSTEM

To demonstrate application of moisture modeling in moisture engineering, the hygrothermal performance of a solid masonry wall was investigated. A two-dimensional heat and moisture transport of 420 mm thick English bond clay brick masonry wall located in Ottawa was simulated. Two cases were examined: one with the wall system totally shielded from wind-driven rain and the other including the influence of wind-driven rain. The details of the boundary conditions, initial conditions and the results of the simulations are presented next.

Boundary and Initial Conditions

Internal conditions were kept constant at a temperature 21 °C and relative humidity 40 % RH (Pv = 997 Pa) throughout the year. The BMY (Best Meteorological Year) weather file of the Canadian city of Ottawa [11] was used in the simulations. A one-year weather file was used for the simulations. The monthly average temperatures and relative humidities for Ottawa are shown in Figure [4]. The simulations started the 1st of July. The yearly average temperature and vapor pressure in Ottawa is 5.6 °C, and 832 Pa, respectively. The total amount of driving rain when temperatures are above freezing (T>0 °C) on a vertical east facing wall (5th floor, center of the wall) is 79 mm in Ottawa. The total amount of precipitation of the year modelled is 570 mm, and the long term (1950-1980) average yearly precipitation is 846 mm [12], i.e., the weather file used in the simulations had less precipitation than the average year in the location.

The modeled wall assumed to be located on the 3rd floor of the building was facing east, i.e., the azimuth angle of the wall was 90 degrees. Dry initial conditions were investigated in this study. The brick and mortar layers were assigned initial relative humidities[2] of 50%. An initial condition RH of 50% corresponds to moisture

[2] Relative humidity in pores of a material is related to moisture content via the sorption isotherm.

content 0.0004 kg_w/kg_d in the brick and the maximum capillary moisture content of the brick is 0.111 kg_w/kg_d. All material properties were taken from the LATENITE Database [Karagiozis et al]. In Figures 4 to 7 the liquid diffusivities, vapor permeabilities, thermal conductivities and the sorption isotherms are displayed for the brick and mortar material layers employed.

TABLE 2--Heat transfer properties for the external and internal surfaces.

Property	External surface	Internal surface
Heat transfer coefficient, W/m^2K	25	8
Short wave absorptivity, -	0.6	-
Long wave emissivity, -	0.9	-

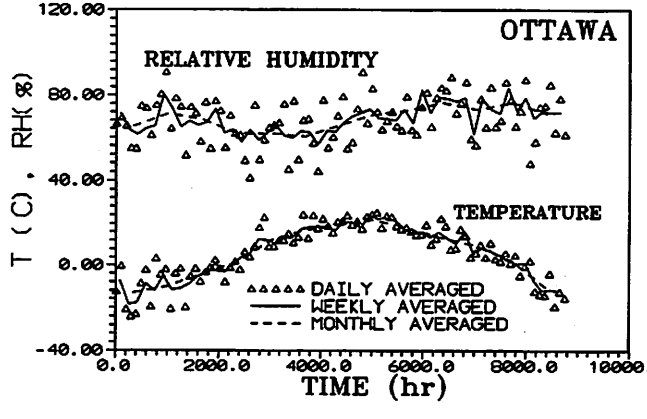

Figure 4: Weather Data for Ottawa used by Model

Results

Moisture Behaviour

Figure 8 shows the 2-D spatial relative humidity distribution after a 60 hr simulation period. Results show that during this 60 hour simulation period the majority of the moisture gradients exist within 70 mm of the exterior surface. The moisture distribution profiles for the brick and mortar layers depend on the moisture transport properties. A characteristic behavior is observed for the red brick which has high vapor and liquid transport properties in comparison with mortar. Figure 9 shows the spatial relative

humidity distribution after 180 hour. The wall system is shown to dry-out after a rain spell and solar heat is drying the moisture inwards. Figure 10 shows the temperature distribution in the wall at 180 hours. A 2-dimensional temperature distribution is present.

Figure 11 shows the transient total moisture in the brick and mortar layers. It is evident that the brick layers accumulate moisture during the simulation period. The mortar layers however did not during the same simulation period. Figure 12 shows the total moisture content of the wall as a function of time, during the July to March simulation period. Results are shown for a wall when driving rain is taken into account, or ignored in the simulations. The results clearly show that rain penetration can be far more important than vapor diffusion when considering heavy masonry structures. Figure 13 shows the effect of moisture transport on the thermal performance of the wall. The weekly averaged heat flux as a function of time is plotted out for the no-rain and rain case. The heat fluxes for the wall that rain was accounted has higher heat fluxes than with the no-rain case. The heating season average difference was found to be approximately 9.4 % higher energy consumption for the wall that wind-driven rain was included in the analysis.

Quantification of important information such as the amount of moisture accumulation and additional heat losses due to allows proper design.

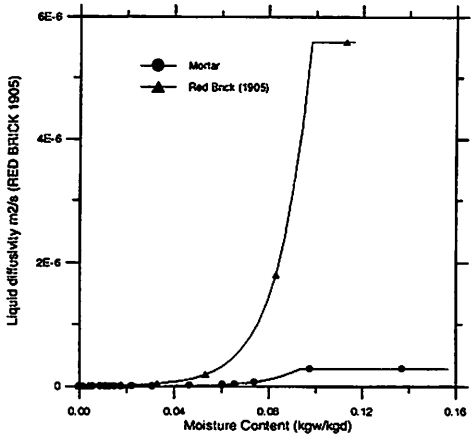

Figure 4: Liquid diffusivity plot

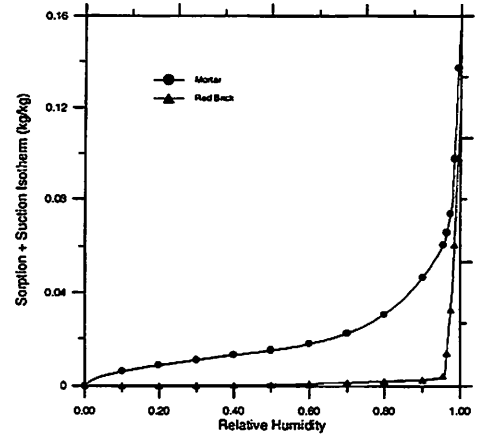

Figure 5: Sorption isotherm plot

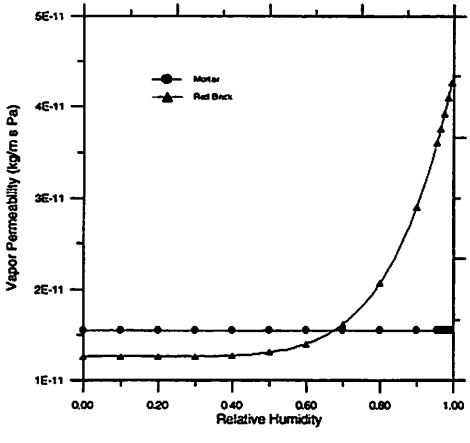

Figure 6: Vapor permeability plot

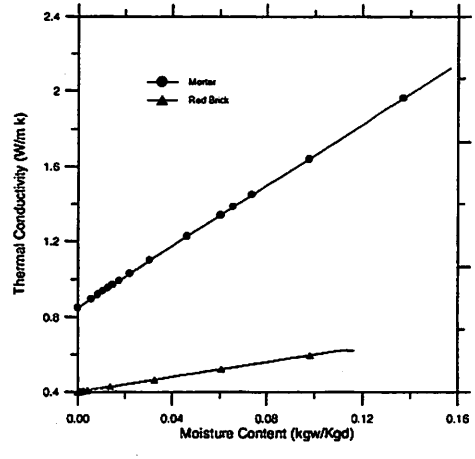

Figure 7: Thermal conductivity plot

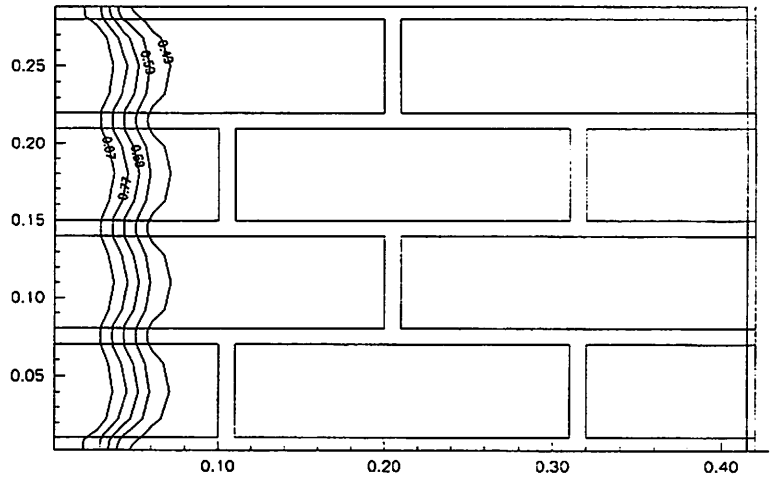

Figure 8: Masonry Wall Relative Humidity Distribution after 60 hr

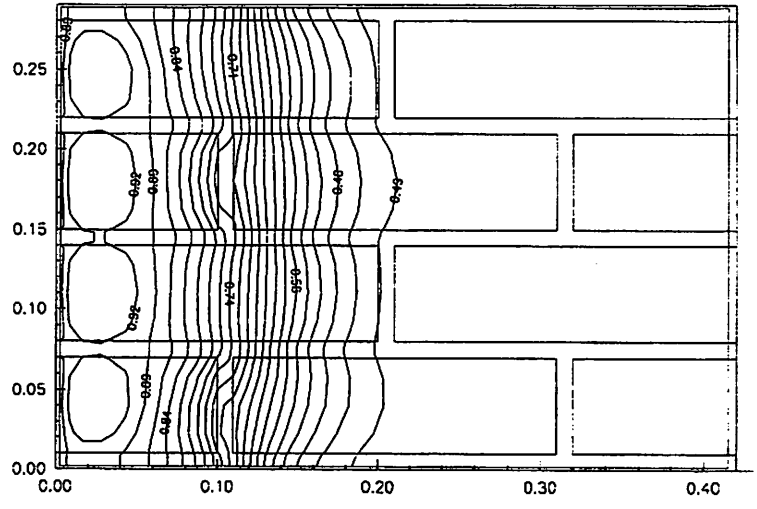

Figure 9: Masonry Wall Relative Humidity Distribution after 180 hr

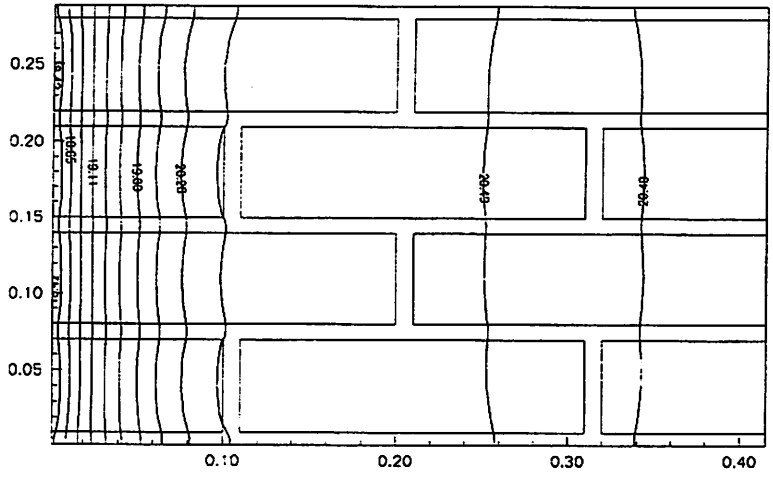

Figure 10: Masonry Wall Temperature Distribution after 180 hr

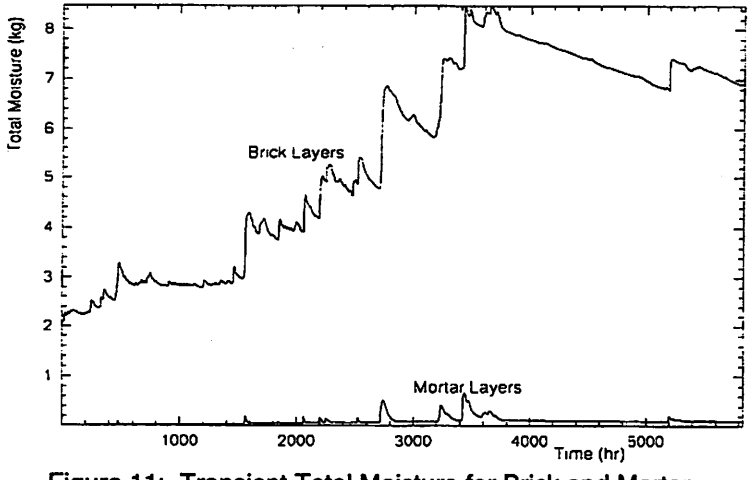

Figure 11: Transient Total Moisture for Brick and Mortar

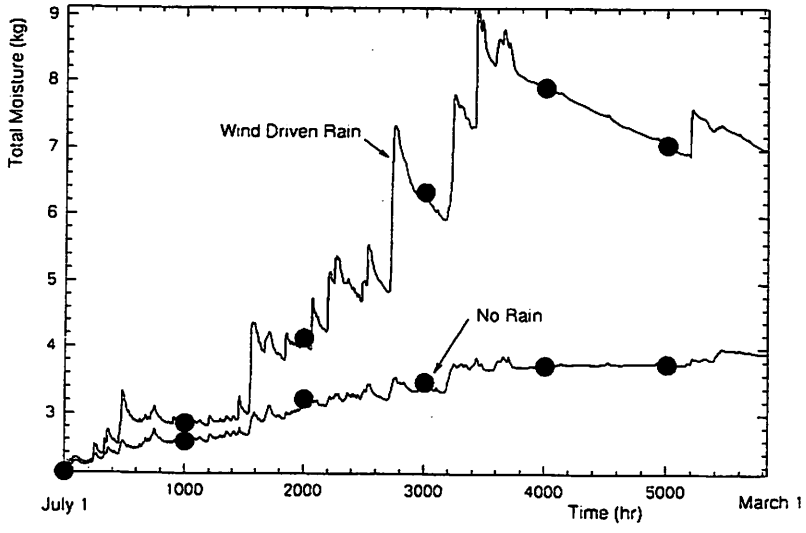

Figure 12: The Effect of Wind-Driven Rain on Total Moisture of Masonry Wall

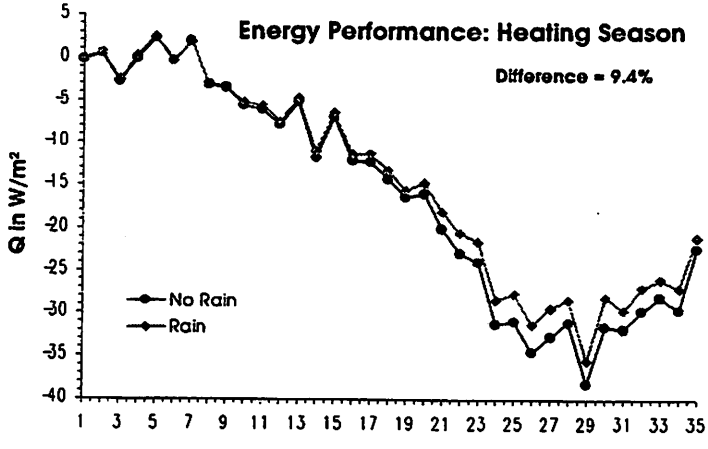

Figure 13: Weekly Average Heat Flux with and without Wind-Driven Rain

CONCLUSIONS

Major advancements in moisture modelig have taken place during the last ten years. Moisture engineering modeling with internal validation checks will be available in the near future for qualified building envelope designers and specialists. System and sub-

system performances of building envelopes can be assessed and optimized to suit the particular preferences and needs of building owners through computer modeling.

Applied moisture engineering by modeling effectively allows one to assess various "what if" scenarios at a fraction of the cost and time required by extensive and time consuming experimental testing. Unfortunately a lot of work is still needed to develop measurement systems to extract in-situ moisture distribution profiles, research in this area should be of top priority. Advanced moisture engineering incorporates the system performance of building envelopes by introducing real defects and systems details from laboratory and field measurements. In addition moisture modeling should be used during the design stage of an experiment, and even during the data reduction to explain and interpret experimental results. Moisture modeling essentially, allows the development of simple design guidelines that are material, system and weather dependent for various building envelope systems.

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Toward Developing Rational Standards for the Canadian Roofing Industry

Abstract:

The roofing industry has witnessed tremendous changes in the way we design and build roofs over the last three decades. Never before have contractors and designers had such a large variety of materials, systems and assemblies to choose from when designing a roofing project. We are told, by some manufacturers that, according to their testing, we can select products that can withstand the harshest extremes of climate and exposure. We have products that, according to claims, will perform in temperatures ranging from well below freezing to near the boiling point of water. They will resist rot, fungal and chemical attack. They will remain flexible for years, are almost totally UV resistant, are unaffected by water and are both abrasion and impact resistant.

Why then, do we continue to be plagued with roofs that leak just a few years after their initial installation? Why is roofing still the primary reason for construction litigation and claims?[1] Our immediate explanation as to the underlying cause might be that our expectations were just overly optimistic, or that in the worst case, we were simply misled by overzealous marketing departments.

If we look more closely however, we will see that each product is usually governed by a material standard that includes a host of tests to determine its properties. We often find that even though these products may not perform as intended, they meet or exceed the criteria established by these tests. The problem, therefore, may not lie in the materials themselves but in the failure to establish a clear relationship between the properties tested and their performance in service. Compounding this problem is the relative imbalance in the knowledge of testing methods, procedures and requirements that occurs between those that develop standards and the end users of them. The incomplete understanding of the requirements within a standard by the latter may lead to involved assumption regarding the purpose and utility as production of performance in-service.

Key Words: Bituminous, insulation, roofing, performance, prescriptive, single ply, shingles and standards.

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Introduction

The roofing industry has witnessed tremendous changes in the way we build roofs over the last three decades. Changes in technology, both in manufacturing and materials have resulted in a deluge of new products for the roofing industry. With these advances has come the need for the user to be much more knowledgeable about the way these products behave once installed and the physics of that behaviour. Ignorance of their performance characteristics can have disastrous consequences for the designer and roofing contractor as well as the consumers of these products.

Roofing contractors are essentially responsible for the physical construction of roofs. Increasingly, however, they are called upon to design roofs as well as install them, particularly in cases of reroofing or restoration of existing roofs. Often there is no designer in these situations and the owner relies on the expertise of the contractor to select and apply the various products that make up the system. In an ideal world, contractors and end users, given sufficient time and resources, could expend the effort to research each product and conduct independent testing to determine their suitability for any specific application. However, few individuals or organizations have the necessary expertise or resources available to do so.

As a result, consumers tend to make selection and purchase decisions based on a form of proxy - Standards. Product and materials standards developed by accredited organizations such as the Canadian Standards Association (CSA), Canadian General Standards Board (CGSB), Underwriters' Laboratories of Canada (ULC) and American Society for Testing and Materials (ASTM) have become substitutes for individual research and investigation. Reliance on standards implies that the properties described and measured in the standards are, to some extent, indicative of the performance attributes of a product for its particular intended use. In our increasingly complex world, accompanied by a proliferation of new materials and rapidly advancing technologies, designers and contractors are increasingly confronted with an expanded array of products to choose from. In order to select the optimal product for a given intended use, however, the decision maker requires information regarding the consequences of his or her choice. As Max Ways stated, "To choose, to decide, requires prediction...every decision-maker seeks to know what, in actuality, the consequences of his choice will be. As the capacity to choose expands, the pressure to predict rises".[2] As the number of products available to the contractor increases, and in the absence of direct experience, so

does the reliance on standards in order to predict their in-service performance.

Prediction is dependant on thorough understanding of cause and effect relationships. This understanding may arise out of direct experience or on the basis of a series of tests that will define basic properties of a material and can be used to simulate the conditions to which it will be exposed in use.[3] Standard testing can be very useful when the relationships between particular physical properties and certain performance attributes are known. The stronger the correlation between the test and the performance characteristics the easier the prediction becomes. By example; it is reasonably understood that there is a strong relationship between low temperature flexibility of a material and its ease of application at cold temperatures.

A high degree of knowledge is, therefore, necessary in order to predict performance based on the requirements included within a standard. Unless one knows the extent of the correlations between the desired properties of a material, and the attributes which are measured and tested, it will be impossible to determine the suitability for an intended use. Standards are, by definition, technical documents that often contain complex, and precise scientific information, related to the properties being measured. The question arises whether the extent of knowledge required to effectively interpret this information is beyond the technical skills of the average roofing contractor.

A standard test cannot apply directly to all particular situations in which a product might be used. Legget and Hutcheon identified the importance of knowledge when they stated the following: "It will always be necessary to take into account the differences between standard test conditions and those pertaining to a particular job application. This is the task for the expert. When knowledge from tests is inadequate, it becomes necessary to rely on experience and judgement."[4] In the face of rapid innovation and the proliferation of new roofing products in many instances the roofing contractor does not possess sufficient experience to assess the relationship between the requirements of a standard test and the products' performance. Closer examination, however, reveals that in some instances there is little or no relationship between the purported test results and the in-site performance of the product.

The increase of new roofing products and materials has been accompanied by an enormous increase

in products and material standards. In the 1970 edition of the National Building Code, by example, there were twenty three (23) standards related to roofing.[5] In the 1995 edition, there are a total of twenty eight (28).[6] Numbers alone, however, do not tell the whole story. In the 1970 NBC, all but three standards (Fibreboard, Polystyrene, Polyurethane) were for bituminous roofing materials reflecting the almost exclusive dependence on bituminous materials for roof construction. In the most recent edition of the NBC, the number of material standards based on traditional bituminous materials has decreased to fifteen (15). The remainder are comprised of newer, non-traditional roof cover materials and insulations. Concomitant with the expansion in standards we are witnessing an increased reliance on standards to regulate all types of building construction, including roofing. Increasingly, by example, the National Building Code of Canada is being used as a "directory" to the use of, and an instrument for giving legal status to these standards.[7]

A cursory examination of many of the roofing standards referenced in the NBC, will reveal that in order to meet the standards, a rigorous regimen of testing and measurement is required. In addition, the physical properties or attributes being measured are assumed to be indicative of a product's ability for in- service performance . In a report titled "Study of Thermal Insulation Standards for Residential Applications" for the Canadian Coordinating Committee for Thermal Insulation Standards and Quality the authors list a total of fifty-two (52) performance parameters identified in the relevant insulation standards alone.[8] Often, the minimum or maximum values appear to be more severe than those conditions to which the product would actually be expected to be exposed to. For example, the minimum requirement for elongation at break for Polyvinyl Chloride (PVC) roofing membrane in accordance with CGSB 37.54-95 is 250% (Types 1&2). It is difficult to envision any normal roof construction other than at expansion joints where this amount of movement and subsequent stress would be expected to occur. More importantly, many of the measured properties may have little meaning for their minimum requirement in service. As Max Baker has pointed out, such characteristics as extensible can be rendered unimportant by a particular method of application. He demonstrated that a thin membrane material may split if solidly adhered to its substrate should cracks appear after its installation, even if the material has 500% or more extensibility.[9] It is imperative, therefore, that the correlation between the properties assessed in the standard, and the in-service conditions be fully understood.

Background

Originally, many standards were designed to meet the needs of local markets or those, like the Canadian Government Specification Board, for a single user group. They usually applied to materials or products that were produced from raw resources in a particular country, manufactured into finished goods, and finally sold to buyers within national markets. As a consequence, many of the standards were written to satisfy the interests of the manufacturers and to protect them from external competition, or in order to reflect cultural and regional differences. Unfortunately, the result has been, in some instances, standards that have little relevance to the performance of these products when used. In addition, the propensity to reflect regional and manufacturing interests have led to a confused array of standards and norms among countries that differ in test methodologies, standards of measurement and properties measured, even though the products may have the same end use.[10]

In this environment of fragmentation and narrow interests, monumental changes are occurring in the world of standards writing. With the advent of mass manufacturing, where single plants of sufficient scale can supply many markets, and with the reduction of transportation costs, facilitating the movement of goods between regions and countries, we find goods freely flowing from one region to another. At the same time, local industries are competing in foreign markets against foreign producers. In the light of FTA and NAFTA, market globalization leads to the dissolution of economic borders and place of origin no longer determine which products are used. The consequence of the internationalization of trade is that many Canadian standards are coming under increased scrutiny and being challenged by our foreign competitors. The best example of this relates to our existing standard CSA A123.5-M90 for fibreglass shingles.[11] The average minimum mass requirement, in accordance with the standard is 4665 g/m^2. The comparable ASTM standard, D3462 requires an average minimum mass of 3564 g/m^2.[12] Although many agree that the latter is too low, particularly when shingles are expected to perform in cold climatic conditions, there is little technical justification for the high values imposed by the Canadian standard. As a result, some foreign manufacturers have complained that the standard is discriminatory and written for the express purpose to exclude an entire class of products, generally known as the 20 year fibreglass shingle from the Canadian market.

The pressure to harmonize standards increases our dependence on their reliability. The roofing

contractor is now often placed in the situation where he must not only make comparisons among materials that have or are being used in the markets with which he may be familiar, but also with products which are produced in different countries with different construction and engineering technologies and produced to standard requirements with which he or she may be completely unfamiliar. In the light of these pressures, the roofing contractor will look increasingly to the relevant Canadian standards to provide the basis for product selection and the information regarding performance criteria necessary for accurate predictions of performance. In order to be effective, however, these standards will have to demonstrate both coherency and consistency. Few roofing contractors have been trained in the disciplines of engineering, science or physics. Standards that do not take into account market globalization or are not easily understood or communicated are of little value to consumers of those goods, be they foreign or domestic.

Insulations

The current confusing and fragmented nature of standards relevant to the roofing industry is best illustrated by those applicable to thermal insulating products. The primary function of an insulation is to perform as a thermal barrier, and to reduce or restrict the flow of heat. As a result, insulations are found in a variety of building elements and are not restricted to the roofing component. When one examines the role of insulations in a roof assembly, particularly in the conventional or compact systems, it is apparent that the properties of the insulation other than their thermal resistivity will have significant effect on the performance of the waterproofing cover. The insulation, in many instances, acts as the substrate over which the roofing membrane is placed or attached. If the insulation fails or is an inappropriate substrate, due to interaction mechanisms, the integrity of the membrane cover may be jeopardized. Judicious selection of a roof insulation is, therefore, of paramount importance in the design and construction of a roof.

Of the thirty three (33) thermal insulations standards in use in Canada, approximately fourteen (14) are applicable to building envelope applications and eight (8) relate particularly to low slope construction. Each Canadian standard identifies performance parameters to be evaluated. However, these parameters vary widely between standards. Some of the inconsistency arises from the nature of the material itself. By example, fungi resistance is applicable only to those materials adversely affected by the form of organic attack.[13] However, a close examination will reveal that many of the

inconsistencies between standards are the result of the disaggregate nature of the way these standards were developed.

These inconsistencies place enormous demands on the knowledge of the user. A high degree of technical expertise is needed in order to be able to assess materials based on the factors included within the standards. By example, three Canadian standards are currently in the process of being updated: polystyrene, polyisocyanurate and glass fibre board. Because of the different test methods it appears that glass fibre has a lower water absorption than the other products. To determine Moisture Absorption, Standard CAN/CGSB 51.31-M84 (Thermal Insulation, Mineral Fibre for Above Roof Decks) refers to ASTM C553 which in turn refers to ASTM C1140/C1104M. "Standard Test Methods for Determining the Water Vapour Sorption of Unfaced Fibre Insulation".[14] The test involves placing conditioned samples into a chamber where they are exposed to test conditions of 49± 2°C and 95± 3° relative humidity for a predetermined period. The criteria in the Standard is that Moisture Absorption is not greater than 0.5% by volume. Standards CAN/CGSB 51.20-M87 (Thermal Insulation, Polystyrene, Boards and Pipe Covering) and CAN/CGSB 51.26-M86 (Thermal Insulation, Urethane and Isocyanurate Boards, Faced) require that the Water Absorption be determined following ASTM D2842, "Standard Test Method for Water Absorption of Rigid Cellular Plastics".[15, 16] This method relies on the buoyancy of materials less dense than water. Conditioned specimens are immersed in water at 23± 2°C for 96 hours. The water absorption by volume is then calculated. Standard 51.26 lists exceptions to this method and the conditioning methods of the specimens are different. The standard for polystyrene requires that Type 4 insulation have a water absorption of less than 0.7% by volume. For polyisocyanurate it is ≤ 3.5% by volume.

Hedlin has shown that many permeable insulations, such as fibrous glass will lose much of their thermal resistance with a small amount of moisture when subjected to repeated cycles of warming and cooling.[17] He also demonstrated that foam plastic insulations gain a greater degree of moisture when subjected to thermally induced vapour pressure gradients than when soaked under no thermal conditions. The testing of insulations under isothermal conditions, may be therefore be questionable in the prediction of an insulation's performance given that in roof assemblies they are most likely to be subjected to significant temperature gradients. To a neophyte in the world of roofing materials or one who does not posses a high degree of knowledge with respect to moisture mechanics, it would appear that fibreglass insulation is more resistant to moisture than either polyisocyanurate or

polystyrene.

When one examines the testing procedures for thermal resistance of the insulations an even more confusing picture arises. Because of different pre-conditioning procedures one cannot effectively compare a variety of available insulations. Depending on testing procedures, a different value will result. By example, standard CAN/CGSB 51.23-92 (Spray Applied Rigid Polyurethane Cellular Plastic Thermal Insulation) requires thermal resistance to be evaluated after conditioning a specimen 90 days at 23± 1°C and 50± 5% relative humidity.[18] The minimum Initial Thermal Resistance is 1.25 m^2 °c/w per 25mm thickness. The aged Thermal Resistance is 1.05 m^2 °c/w per 25 mm thickness. The standard notes that Thermal Resistance values are not to be used for design purposes but only for specification of the material. Standard 51.26 requires Thermal Resistance to be evaluated after conditioning the specimen 28 days at 100± 3°C. The oven aged Thermal Resistance for both the 25mm specimen and a calculated thermal resistance of a one metre thick specimen are to be reported. The oven aged thermal resistance for Type 4 material is to be ≥ 1.00m^2 °c/w for 25mm thickness. The result of these variances in test methods for determining thermal resistance of the particular insulating materials is that a direct comparison of their thermal properties, based solely on the test results is virtually impossible.

The variance in conditioning and testing procedures are, to a great extent, necessary due to the different physical properties of the materials being tested. When a standard is intended to characterize a material, the test results for one product, comprised of that material, can be useful when comparing the test results of another products comprised of the same material.[19] Differing test methods may also be informative if the standard is intended as a simplification in the interest of standardization. By example, calling up certain grades of products, by agreement, may constitute a standard. However, increasingly roofing contractors view standards as a means to compare the performance characteristics among different products. In these instances, standards may have to be expanded to include different test procedures, or more complex test methods may have to be developed which universally apply to a variety of materials. Currently, most contractors do not possess the expertise or knowledge to comprehend the importance or consequences of different conditioning procedures and measurement methodologies. As a result, confusion exists making it difficult for the contractor to compare the long term resistivity among the various insulating materials. This places an undue

liability on the contractor, particularly in the absence of a professional designer, as often is the case in reroofing projects where the contractor is the designer. In order to mitigate the contractors' responsibility for determining long term thermal resistance, the Canadian Roofing Contractors' Association has issued an advisory bulletin recommending that its members refrain from basing bids on R-values,[20] using thickness instead.

Phenolic Insulation

An issue which has come to the attention of building owners, designers, and contractors throughout Canada relates to the use of a particular type of cellular plastic foam insulation known as phenolics. Although there are no manufacturers of this material remaining in Canada (the three manufacturers exited in industry in the early 1990's) the relevant standard CAN/CGSB 51.25-M87 (Thermal Insulation, Phenolic, Faced) remains in force and continues to be listed in the NBC.[21]

Problems with this type of insulation first surfaced in 1990 in the form of reports of severe steel deck corrosion occurring on roofs incorporating phenolic insulations.[22] At first, the problems appeared to be limited to the United States where a large number of roofs are constructed without a vapour retarder and steel decks are prime painted as opposed to galvanized protected. The extent and severity of the problems resulted in one manufacturer publishing Product Alert Bulletins in an attempt to identify buildings on which this insulation had been used.[23] In 1995 incidents of similar corrosion were observed in Canada and a Canadian manufacturer published a similar advisory alert.[24]

The potential for corrosion was recognized as early as 1982.[25] In 1985, a laboratory evaluation for a phenolic manufacturer which compared the corrosiveness of various insulating materials indicated the potential for corrosion of steel decks to occur under certain conditions.[26] The Canadian Standard for phenolic insulation, CAN/CGSB-51.25-M87 contains an article (8.5) that states that "Phenolic foams may contain some corrosive compounds. When it is anticipated that the foam will be in direct contact with metal, the supplier shall provide the proper installation procedure."[27] In 1989, ASTM material standard ASTM C 1126-89, "Standard Specification for Faced or Unfaced Rigid Cellular Phenolic Thermal Insulation" for phenolics was issued, containing a statement that phenolic foams may contain some compounds that may promote corrosion in the presence of liquid water.[28] Although these statements alert the reader to the potential of corrosion occurring, they provide little information as to the consequence in the selection of a phenolic product, the extent to which

corrosion may occur, or the conditions which may promote it. Without this information it is impossible to predict the consequences of the use of these materials in a particular use. In the absence of a standardized test to measure the amount of corrosion, under a specific set of conditions, prediction becomes impossible. To be of any value, such a statement must be accompanied by a practical and reproducible test method in order to assess the degree of corrosion that may occur given anticipated in-service conditions. As Legget and Hutcheon have pointed out, a test method alone is insufficient. " It must be supplemented by guidelines as to range of values between which test results should lie for satisfactory performance.[39]

PVC Roof Membranes

In January 1979, CGSB developed the first Canadian standard for Sheet applied Polyvinyl Chloride roofing membranes.[30] The requirements of the standard were based on product data that were available at the time. Under the Paragraph 3.1.1 two types of membrane were described in the standard. Type 1 consisted of a non-reinforced membrane whereas Type 2 consisted of a reinforced membrane. In accordance with the standard, both types were suitable for use as a roofing membrane.

In the 1980's problems were reported with roof systems incorporating the non-reinforced membranes. These problems were associated with severe embrittlement of the membrane, resulting in spontaneous shattering, particularly at cold temperatures.[31] The problems were described as being catastrophic in this sense that the shattering involved the loss of waterproofing integrity of expansive areas of roofs. The instances of this shattering were reported as early as 1983 and increased steadily over the next number of years.[33]

The largest proportion of problem roofs reported were located in the United States where the extent of the phenomenon was investigated by the National Roofing Contractors Association (NRCA).[33] The governing standard for PVC membranes in the United States was the ASTM Standard D4434, "Standard Specification for Poly (Vinyl Chloride) Sheet Roofing."[34] Similar to the Canadian standard, both reinforced and non-reinforced membranes were included within the standard. As the incidence of shattering were limited primarily to the United States, the question arises as to whether the Canadian standard included more stringent, or contained different requirements that limited the use of materials prone to shattering to be used in Canada. A comparison of the two standards will quickly

reveal that the dearth of shattering problems in Canada was not related to notable differences between the standards, but as a result of market share among manufacturers. As it happens, most of the PVC membranes used in Canada were manufactured by producers who marketed reinforced membranes whereas a substantial number of roofs in the United States were constructed with non-reinforced membranes.

More importantly however, the research conducted by Smith, Paroli and Whelan indicated that although the catastrophic shattering failure was exclusive to non- reinforced membranes, the loss of plasticers which contributed to the shattering was not limited to non-reinforced membranes.[35] The embrittlement can occur equally in reinforced membranes. However, the reinforcement provides a matrix which holds the membrane together. So although catastrophic shattering will be prevented, enbrittlement can lead to micro cracking, or crazing, and result in the loss of the ability of the membrane to act as the waterproofing barrier. The research further revealed, through dynamic mechanical analysis, that there were significant differences in the physical properties between the PVC specimens from shattered roofs and the control specimens, or those that did not exhibit the embrittlement. The authors found that a change in the glass transition temperature (Tg) of the material was indicative of a significant change in the material's physical characteristics which would be useful in predicting the likelihood of shattering occurring.[36]

Widely accepted as a useful measurement of the change in the properties of a membrane material, and therefore its ability to perform as an effective waterproof barrier, it was recommended by some that the Tg be included in the PVC standard as it was being revised in 1995.[37] The inclusion of a test and measurement of the Tg was resited by the Committee members, ostensibly on technical grounds. In lieu of this requirement a weak reference to Tg was added which reads "The use of glass transition temperature (Tg) as criterion for specification of PVC membranes shows great promise for future incorporation into this document."[34] Subsequent to the revision of this standard, the Joint Committee on Membrane Roofing Systems released the final report of its Thermal Analysis Task Group (Rilem 120-MRS/CIB W.83) in which it stated:

> "Tg is an acceptable method for characterizing new and aged roofing membrane materials. This complementary to other mechanical, chemical, and physical methods used for membrane material characterization. It may be used for a variety of

applications such as evaluating stability under laboratory and outdoor exposure, or providing quality control measurements."[35]

It is difficult to justify the exclusion of such a reliable method for determining a change in the properties of a material, between aged and unaged specimens in the new standard. The inclusion of Tg would not only serve to provide the contractor with information regarding the potential performance of the product in-service but would also be a valuable tool in assessing the condition and potential for shattering of an installed PVC roof. Contractors are routinely called upon to assess the condition of existing roofs and to determine whether they are candidates for "shattering". A clearly defined Tg requirement would facilitate this assessment.

Bituminous Roofing Standards

Many of the current bituminous roofing standards were developed by the Canadian Standards Association. Both the standard for "Bitumen for Use in Construction of Built-up roof Coverings and Damproofing and Waterproofing Systems" (A123.4-M1979) and the standard for roofing felts "Asphalt Tar Saturated Roofing Felt"(A123.3-M1979) published in 1979 were reaffirmed as in 1992.[39,40] Their reaffirmation implies that the standards were relevant, current and technically sound. However, a detailed examination of the standards will reveal the anachronistic nature of these two standards.

Asphalt remains one of the most important elements in conventional built-up roof construction. Since the late 1970's, considerable research on bitumen used for BUR has led to the adoption of EVT (Equiviscuous Temperature) as the measurement for determining the correct temperature for their application. Prior to the development of the EVT concept by industry contractors and producers relied on such performance properties as softening point and penetration, combined with application quantities per unit area to ensure that the appropriate type and coverage of asphalt was achieved for a particular application. Although EVT is now a fundamental principle embedded in the lexicon of roofing technology and specifications, it is conspicuously missing from CSA 123.4. One must question the relevancy of this standard when it fails to reflect this critical advance in roofing technology.

Even more surprising was the reaffirmation of the Asphalt Felt Standard in 1992. There are two types of felts listed complete with associated physical requirements - Organic felts and Asbestos felts. Asbestos felts were used to some extent in built up roofs in Canada during the late 1970's and early 1980's. However, due to extensively reported problems with splitting during cold temperatures most products were withdrawn from the market. As a result of their poor performance, coupled with concerns related to health and safety has resulted in asbestos felts have not been used in BUR roof construction in Canada for well over a decade, yet they remain listed as acceptable products within the standard.

In fairness, all of the Bituminous Standards currently the responsibility of CSA are under review or revision. It is expected that both the felts and the bitumen standards will be revised to reflect current technology and industry practices. By example, it is expected that the reference to Asbestos felts is to be deleted from CSA 123.3, reference to EVT will be included in CSA 123.4, and both revised standards will omit reference to coal tar. It must be understood, however, that the current activity with regard to CSA bituminous standards is not a result of industry demand for updating the standards but in response to CSA's proposal to withdraw CSA roofing standards entirely due to the lack of industry interest.

Single Ply Membranes

Roofing materials standards in Canada have, for the most part, developed in an ad hoc manner resulting in a body of disaggregate, fragmented and inconsistent standards based on manufacturers' purchase specifications. Of the many chemical species of single ply membranes currently used in the roofing industry, including thermoset elastomeric, chlorinated polymer membranes, polyolefins, copolymer alloys, terpolymers, interpolymers, and oligemers, only PolyVinyl Chloride (PVC) and Ethylene Propylene Diene Terpolymer (EPDM) are governed by standards from an accredited Canadian standards organization.[34] Although there are differences in the chemical compositions of the plethora of new single ply products available, and therefore, their mechanical and physical properties, it can be argued that there are more similarities than differences. With respect to performance requirements of synthetic single ply membranes, Dr. Rossiter identified sixteen (16) performance parameters that are widely accepted as being common to all.[39]

In order to eliminate much of the confusion regarding these materials, the industry has chosen to bifurcate them into two broad divisions - plastomeric and elastomeric. Considering that the performance requirements are unlikely to differ significantly between the particular materials that fall in each division, an attempt to develop a omnibus standard for each should be considered. The result of such action would be the elimination of the confusion that currently exists among the end users, especially contractors with respect to performance requirements and attributes. In addition, this would provide a means whereby new products that are entering the market with increased rapidity can be readily assessed and compared.

There are, however, many impediments to the evaluation of new products through the use of existing standard test methods. Standards are normally developed on the basis of knowledge of the attributes of a known product and its intended use. These same standards may, therefore, may not be valid for a new product or for some application that is abnormal. In addition, although standard tests can be helpful, they should always be backed up by other evidence, such as experience, or proof of previous satisfactory performance. Such proof is usually not available for new materials. As a result, the need for knowledge, and technical expertise to assist in the interpretation of test results becomes even more important.

The Road Ahead

The move to omnibus standards, in all fields of the roofing industry, is an onerous task. By definition, in order to be useful, such standards must shift from the current manufacturer specification standards to user based standards. This would involve the review and reconciliation of the existing standards and test methods to determine which can be combined, and what criteria relates to performance of the product. A high degree of technical expertise would be required to carry out this task. Genge, in his study on residential insulation standards suggested a number of technical issues requiring change. These include the need to eliminate subjective criteria; to eliminate vague and inconsistent nomenclature and terminology; to standardize end use performance parameters and to standardize test methods.[42]

Recently, several initiatives at achieving these objectives have been undertaken by a variety of groups representing the roofing industry in Canada. In 1993, the Canadian Coordinating Committee on

Thermal Insulation Standards and Quality now called the Thermal Insulation Systems: Standards & Quality Steering Committee was formed. Consisting of representatives from associations of insulation manufacturers, industry associations and government and research organizations, the primary objective of this group is to review the existing insulation standards for the purpose of initiating the necessary changes required to harmonize and rationalize them wherever possible. Its formulated mission was as follows:

> "To improve the quality of Canadian standards for thermal insulation and to implement a more efficient system for writing of these standards".[43]

Since the creation of TISSQ, some progress has been made with respect to the achievement of these goals. Steps are now underway to rationalize and harmonize the existing standards. All standards have been prioritized for review and revisions, and in order to achieve the long term goal of harmonization. As the standards are being revised they are being compared against one another in order to reconcile the various test methods, terminology and performance parameters. One of the most important activities of this Consortium is the development of a User Guide to be available to designers and specifiers, contractors and building owners. This guide based on common designs and applications and their associated performance requirements will provide the readers with information, in plain language, necessary to select the appropriate materials for a particular end use among all the available alternatives. The guide will also provide a framework for better standards as they are being developed or revised.

An equally important development is occurring with regard to the Canadian standard for modified bituminous roofing membranes. Last revised in December 1985, the CGSB standard 37-GP-56M (Membrane, Modified, Bituminous, Prefabricated and Reinforced for Roofing) is currently under revision and close to final ballot.[30] Although the high quality of this standard has been recognized by the entire roofing community, it suffers from a weakness which compromises its utility for the consumer. This weakness is based on the failure of the standard to accurately reflect the way most modified bitumen roofs are built. In Canada, the vast majority of modified bitumen roofs are constructed as composite systems, usually consisting of a minimum of two (2) layers of membrane. As a result, the strict attention to the properties of a single membrane, or layer, does not allow the designer or contractor to make his of her material selection based on the performance requirements

of the system as opposed to the particular single membrane component.

Included in the current standard is the minimum requirement for a product load strain product (product of breaking strength and ultimate elongation). There are numerous membrane sheets available that are unable to meet the standard for these properties but have proven to perform well when used in a membrane system. To accommodate these materials it is hoped that the new standard will define the membrane as the finished built-up waterproofing layer comprised of one or more prefabricated sheets. In addition, the revised standard proposes that if one sheet of a multi-ply membrane meets the strain energy requirement of the standard, the membrane shall be deemed to have met the requirements. As opposed to single component requirements, the membrane as a system can be tested. This will provide the designer and user with the flexibility to choose from an array of available products. As long as the products meet the requirements either singly, or in combination, they will conform to the standard. This shift from single component to system requirements represent a fundamental change and is a first step towards predicting the performance of the membrane system.

Even in the area of more traditional roofing materials, some progress is underway. In response to the proposal by CSA to withdraw all bituminous roofing materials standards, industry representatives rallied in support of both the maintenance of CSA standards and the need for Canadian standards in general. The reconstituted A101 Technical Committee on Bituminous Roofing Materials, has been at work attempting to rationalize and revise the current standards to reflect current industry practices. Where appropriate, this rationalization involves the withdrawal of CSA standards in favour of adoption of the appropriate ASTM standards. The most notable example is the proposed withdrawal of CSA standard A123.17 (Asphalt-Saturated Felted Glass Fibre Mat for Use in Construction of Built-Up Roofs) and the recommended adoption of ASTM D2178 (Standard Specification for Asphalt Glass Felt Used in Roofing and Waterproofing).[45,46] The Committee members, through the feedback from their constituency realized that harmonization, or the simple adoption of other recognized standards, such as ASTM was not appropriate in all cases. Where the differences in the production of roofing materials as in the case with asphalts between US and Canada, the adoption of the ASTM standards impractical and the existing standards are being revised.

In some instances it is recognized that, due to particular climatic and geographical conditions, a

specific Canadian standard is necessary. This is the case with fibreglass shingles in particular. Although there is consensus that the mass requirements in the current CSA standard CAN/CSA A123.5 may be excessive, it was also agreed that any standard should reflect the performance requirements of service for the Canadian, or cooler North American climate. The occurrence of cracking and splitting problems, prompted the Committee to consider developing a standard for shingles suitable for "Cold climates". Currently, the committee is also attempting to amalgamate the organic and glass shingle standards into one document, specifying requirements, based on performance criteria as opposed to material properties. It is hoped that the final product of these efforts will be a comprehensive set of standards for bituminous roofing materials that will meet the requirements of service in cool northern climates such as our own.

Conclusion

There has been much criticism of materials standards related to roofing products in Canada. Some have argued that development of performance, as opposed the prescriptive standards, will resolve many of our current problems. However, as Legget and Hutcheon have stated, this belief appears to take for granted that "there will be no difficulty in establishing suitable statements of performance requirements."[47]

Performance requirements can be stated in many forms with varying degrees of specificity. A general requirement, without a measurable level of performance is practically impossible to interpret or enforce and, therefore has very little utility for the user. Performance requirements must be expressed in measurable terms to be of any use. Often, however, knowledge simply does not exist to permit the development of definable or measurable levels of performance. One solution has been to establish performance levels by measuring the characteristics of one material and comparing it to the measured characteristic of another that has been known to provide satisfactory performance. Even this method has its shortcomings. As roofs behave in a dynamic fashion and the performance of one component is largely dependant on its interaction with others, a single measured characteristic may not provide sufficient information to predict performance in service. When more than one factor needs to be assessed, it is always difficult to determine what combination of factors represent the conditions that reflect probable performance. The challenge is, therefore, to develop a consensus as to what the criterion for various roofing materials should be.

Establishing performance criteria for roofing materials and systems will prove to be a monumental task. Often the impediments are the result of the lack of generally accepted criterion or the difficulties associated with devising satisfactory, economical and reproducible tests. As early as 1974 W.C. Cullen and R.G. Mathey published their pioneering work BSS55, "Preliminary Performance Criteria for Bitunimous Membrane Roofing".[48] This publication promulgates twenty performance attributes required for the successful performance of built-up roofing membranes. Although widely accepted as a major step towards performance standards, two decades later their criteria remain preliminary.[49] In the light of this slow pace, the development of performance standards must continue to be complemented by prescriptive requirements.

Although much effort will have to be given to the development of rational and useful standards in the roofing community, work being carried out by such groups as TISSQ and the CSA Technical Committee A101 give cause for optimism. In order to render any standards useful, performance parameters must relate to the materials application and end use. The attempts by the aforementioned standards committees to standardize terminology, eliminate testing parameters that do not relate to end use are a first step to addressing much of the criticism related to our existing roofing standards.

Among the issues requiring consideration by those involved in the standard development process is the need for achieving the proper balance of individuals with a high degree of knowledge and expertise in the area of test procedures and methods, usually requiring considerable training and education in the sciences and engineering, and the end users of the standard who should have practical knowledge and experience with the end use conditions of a material and its application.[41] This balance is increasingly difficult to achieve given the current scarcity of resources available to most roofing contractors. Many simply do not have the time, or financial resources needed to actively participate in the writing of standards. Even when they do, few possess the training necessary to understand and assess the quality or validity of test methods and the measured results. I myself can appreciate how intimidating the standards committee environment can be when matters relating to testing procedures and scientific measurement are discussed. Even the language of discourse, complete with technical jargon, is difficult to comprehend without a minimum level of training in the scientific disciplines. In order to increase the participation of the end users, and particularly the roofing contractors, efforts must be undertaken to simplify the language of the

standards or at least provide clear definitions and consistent terminology to promote discussion between the two groups. I would suggest that a simple starting point would be to include a glossary within the standard that would, in plain non-technical language, describe a qualitative statement of the specific requirements, the particular test method, and a commentary explains the reason or intent of the criterion. Caution would, of course, have to be exercised so that these definitions do not vary significantly from standard to standard. In the long term, consideration should be given to the development of a "users guide to roofing standards" which would incorporate descriptions of the various test methods, and their relevance with regard to in-service performance.

A major impediment to developing standards relevant to the roofing industry is that standard display many of the features of a true "collective" or "public good", in the sense that no one can be prevented from consuming the benefit of the standard even though they have not contributed to its production. As a result, a large number of those who ultimately use or rely on standards behave as "free riders". Although they derive benefit from standards in the selection of products and prediction of their performance, many choose not to participate or expend any energy in their development, relying instead on others to do the work. As a result, many standards do not have the depth or range of representation needed to assure that producers and end users alike take responsibilities for the production of standard. In addition, even though the roofing community as a whole, benefits from the development of quality standards, the public good problem promotes the tendency for those who have the biggest interests, or share of resources, to disproportionately participate in their production. In this instance product manufacturers, for competitive interests, are more likely to be actively involved in standards writing than are end users. Roofing contractors, must be encouraged to participate in the standard writing process from the inception stage to completion, and remain actively involved in their maintenance if the desired balance of representation is to be achieved.

With respect to the paucity of resources available to the individual roofing contractor for standards work, this may be overcome by the participation of representatives of various collective bodies, such as trade associations. This may also pose difficulties as this approach leads to the assumption that all of the members of a particular association will be in unanimous agreement. In addition to placing a disproportional burden on the appointed representative it may not be equitable in that the

association will be viewed as a single entity as opposed to a number of independent organizations when the proposed standard is balloted. Nevertheless, participation by the end users, specifically roofing contractors, is essential if we are to produce standards of high quality, that truly reflect performance requirements of materials for their intended use.

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Roof Ice-Dam Research: Problems and Solutions

Ken Ruest and Anil Parekh

Abstract

Ice damming generally occurs when the roof surface temperature is just above freezing over the attic space and below freezing at the eaves. Ice damming sometimes causes water leaks which may damage the insulation as well as structural components. The winter of 1995-96 presented unusually favourable conditions for roof ice-dams in several Canadian cities.

As part of CMHC sponsored research, a detailed investigation of 33 houses was undertaken to study the effects of ice-dams. The main objective of the study was to evaluate various parameters affecting the formation of ice dams on roofs. Various types of roof structures were selected. Attic temperatures and indoor air temperatures were monitored for a period of two weeks. The field work also included a detailed survey of attics and roofs of 33 sample houses.

The study found that houses which experienced ice damming had attic temperatures about 4°C warmer than houses which did not experience ice dams. It was also observed that almost half the number of houses which experienced ice dam problems had significantly lower levels of insulation — about 20% less than the building code requirement at the time of construction. Air leakage at the chimney penetration into the attic was suspected to be a major source of heat into the attic. Poor soffit venting due to blocked or insufficient number of insulation baffles and narrow roof overhangs seem to be major causes of warmer attics. The study emphasized the need for proper levels of attic insulation, adequate ventilation of attic spaces and proper detailing of roofing at valleys, chimney boxes and edges.

Key Words

ice-dams, roofs, attic temperatures, attic insulation, moisture problems, water leakage from roofs, and eaves protection.

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Roof Ice-Dam Research: Problems and Solutions

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Background

Roof ice damming is not usually as widespread as it was during the winter of 1995–1996. The combination of significant snow accumulation on roofs and relatively cold temperatures in the early part of the winter contributed to the formation of ice dams. Typically, ice damming problems become epidemic during winters when there is high snow accumulation and sustained below freezing ambient temperatures. Such conditions were experienced during the December 1995 in Ottawa, Montreal, Winnipeg, and Edmonton. During December 1996 and January 1997, numerous incidents of ice-damming were reported in BC and western Canada due to high snow falls and sustained cold temperatures.

Ice damming generally occurs when the roof surface temperature is just above freezing over the attic space and below freezing at the eaves. Ice-damming sometimes causes water leaks which may damage the insulation as well as structural components. It should be noted that the ice-damming in itself is not a problem; it is the resultant water leakage due to ice dams that causes building performance problems. Water leakage from ice-dams could affect the building performance in the following ways [1]:

- failure to keep building components dry
  - wet attic and wall insulation (ruined attic insulation; especially if cellulose fiber)
  - interior finish damage (ceilings, walls, flooring)
- reduced thermal performance of assemblies due to wetness
- mold growth and wood rot if wetness persists for extended periods of time in cavities

Other problems caused by ice-dams include the following:

- damaged roofing (mostly due to people trying to break the ice with axes etc.)
- significant ice build-up may cause structural damage to the eaves and the roof
- falling icicles are a potential safety hazard to passersby
- people falling off roofs when trying to shovel off the snow (safety concern)

Unusually severe weather conditions can highlight some weaknesses of current construction practice both in existing as well as in new housing. Existing houses have suffered wide-spread ice-damming problems due to lack of eave protection and generally lower levels of attic insulation. New houses, with better attention to air sealing, adequate amounts of insulation (RSI

5.64 or more), mandatory installation of eave protection and attic ventilation, should not suffer from ice damming problems; yet many do.

The Canadian Home Builders Association (CHBA) recognizes ice damming as a widespread problem. The Ontario New Home Warranty Program (ONHWP) has faced high numbers of claims from ice-damming problems during the last three to five years. Insurance companies reported a large number of complaints in existing houses which had never had ice-dam problems in the past [2]. The Research Division of Canada Mortgage and Housing Cooperation initiated a research project to investigate why some new houses suffered from ice damming, while the majority escaped damage [3].

The main objective of the project was to study and evaluate various parameters affecting the build-up of ice-dam on roofs. As part of the field investigations, houses built during the period 1991 to 94 were selected. The sample size included 16 houses which experienced ice-damming problems and 17 houses which did not experience such problems. This paper focuses on the field observations, the identification and evaluation of conditions which induce ice-damming, and briefly suggests some solutions.

Mechanisms

Ventilated sloped roof systems are vulnerable to moisture from three sources: rain penetration, water vapour, and ice damming. Certain basic building science principles relating to moisture problems must be understood to be able to improve the durability of roofs. The causes of roofing problems may be traced to poor roof design, the materials selected by the builder or designer, and most importantly, how it is put together during construction and how it is maintained. Ice dams cause moisture damage only when the shingles and roof sheathing allow water to penetrate into the attic or wall spaces.

The Process of Ice-Damming

Ice-damming is the build-up of ice at the edge of the roof, caused by heat from the house melting the snow on the roof and the water refreezing when it reaches the colder portion of the roof over the eaves. The following factors are necessary for ice-dams to form:

- snow accumulation,
- heat from the house or building to melt the snow, and
- cold temperatures to freeze the melted snow into solid ice over the eaves.

As little as 5 to 8 centimeters of snow accumulation on a roof can cause ice dams to form. Snow on the upper part of the roof melts, runs down the roof under the blanket of snow to the edge of the roof, and freezes into a dam of ice. Eventually, water may back up behind the ice dam, under the shingles and penetrate into the structure. Figure 1 shows a typical sketch of ice dam.

Why do ice-dams usually form along the roof's edge? Conductive heat loss through the ceiling and/or warm air leaking from the interior of the house or building, warms the roof sheathing if the attic ventilation cannot exhaust the heat fast enough. The melting snow trickles down to the cold roof edge (above the eaves) and freezes. The snow on the roof adds some insulating value to the roof (about 0.07 RSI per centimeter of snow) which helps the heat in the attic space to raise the surface temperature of the roof sheathing which further promotes snow melting at the roof surface. Eventually, a layer of ice forms on the roof sheathing above the ice dam and traps the melting snow between the ice slab and roof shingles. The layer of ice can extend upward several meters from the edge of the roof. We have observed that this ice slab can extend about 1.5 to 2 meters in some houses. This distance is greater than 0.9 m of eave protection minimum required by the OBC and the NBCC codes.

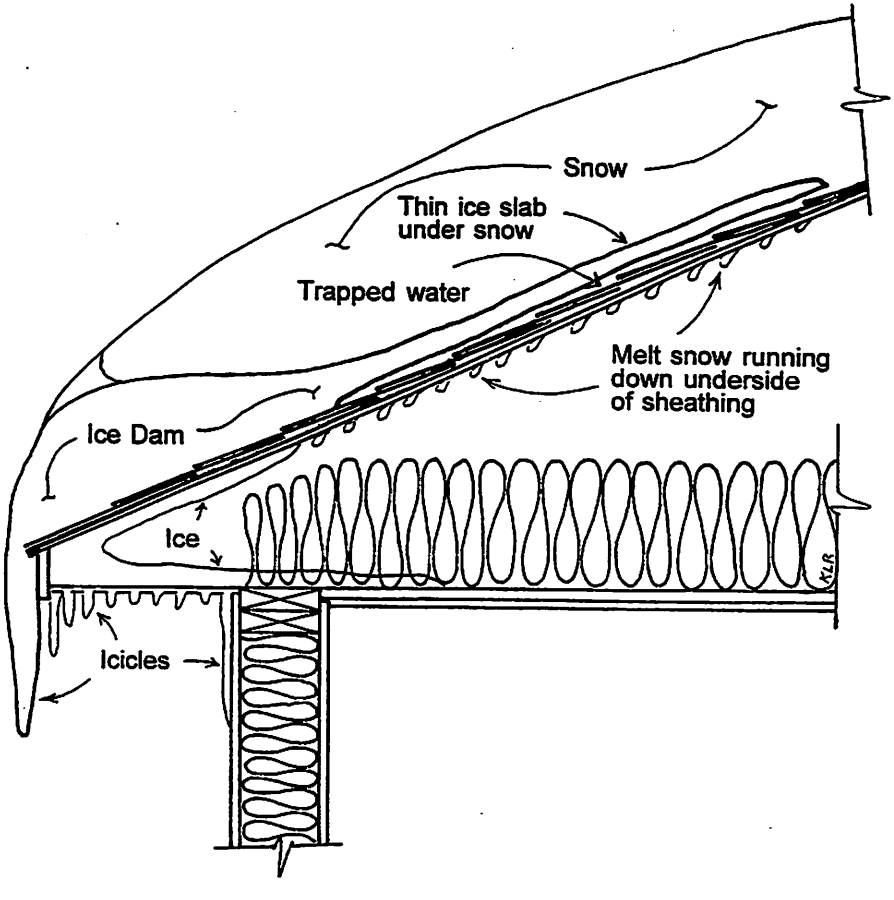

Figure 1: Typical sketch of an ice dam.

Prediction of Conditions Favouring Ice-Dams

To predict the initiation of ice dams on the roof, one would require the following information:

- the thermal characteristics of the attic space (insulation levels, ventilation rates and attic space temperature);
- the thermal characteristics of the roof (insulation level and surface temperature);
- the ambient conditions (outdoor wind speed, air temperature and solar insolation); and
- the snow accumulation.

There is a significant knowledge base available concerning effects of heat, air and moisture movement in roofs and attic spaces. The attic heat loss model used in HOT-2000 determines the effects of heat losses through the ceiling (attic floor), air change in the attic through vents, and heat losses from the roof. The calculation procedure determines the attic temperature [4]. During 1991 to 1993, Forest and Walker, from the University of Alberta, developed an attic simulation model to predict attic ventilation rates and their effect on temperature and moisture distribution within an attic [5]. The study showed that attic ventilation significantly affects moisture levels in attic spaces. The code requirement for roof vent area of 1/300th the attic floor area is adequate to mitigate the moisture problems. The ASHRAE Handbook of Fundamentals gives a simplified method to determine the attic space temperature [6].

Effect of Insulation: The roof surface temperature can be determined using a simplified one dimensional approach:

$$T_{roof} = T_{out} + (T_{in} - T_{out}) * \frac{RSI_{snow}}{RSI_{total}}$$

where, T_{roof} = surface temperature of the roof
T_{in} = attic space temperature
T_{out} = ambient temperature
RSI_{snow} = RSI value of snow (about 0.07 m^2K/W per centimeter of accumulated snow)
RSI_{total} = RSI value of roof assembly and the snow

Using the available calculation procedures, two simplified illustrations are presented in Figures 2 and 3. The greater the thermal resistance of the attic and roof assembly, the greater the snow build-up that can be tolerated before melting conditions occur at the roof surface. For an existing house with about RSI 3.52 (R-20) insulation, the roof surface temperature will rise to above 0°C with a 10 cm snow accumulation and an outdoor temperature of about -10°C. The roof surface temperature is sufficiently warm to melt the snow. The outdoor temperature is sufficiently low to freeze the water at the edge.

Effect of Attic Ventilation: The attic ventilation rate is a key parameter in reducing the probability of ice formation on roof surfaces. A detailed analysis was undertaken to evaluate the effects of attic ventilation. The calculation procedure considered the effects of the attic and roof thermal characteristics, solar insolation, wind and the indoor and outdoor temperatures. Figure 4 shows an example of a profile of roof surface temperatures. In this example house, the attic is insulated to a level of RSI 5.64 (R-32). The roof is covered by about 10 cm of snow and the outdoor temperature ranges from -8°C to -13°C on a relatively clear and sunny day. As shown in the figure, with a minimum ventilation of 0.5 L/s.m^2 of attic floor area (about 1.2 air changes per hour), the roof surface temperature is above 0°C for about 6 hours, causing the snow to melt. The outdoor temperature is sufficiently low to freeze the water at the edge thus forming an ice-dam. The simulation results show that by increasing the ventilation to 1.5 L/s.m^2 of attic floor area (3.6 air change per hour), the roof surface temperature drops well below the freezing mark at all times, thereby avoiding the snow melting.

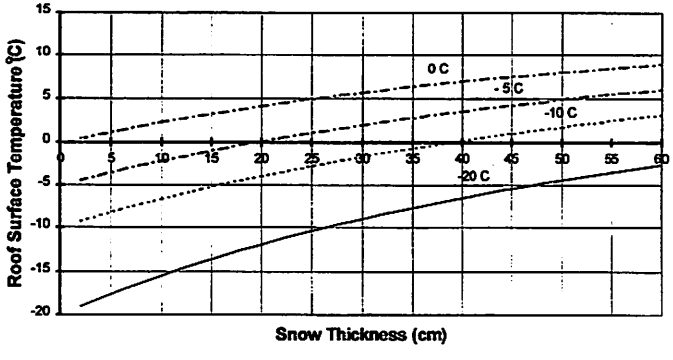

Figure 2: Estimated roof surface temperatures for various outdoor temperatures for a house with RSI 5.64 (R-32) attic insulation, as found in most newly constructed houses.

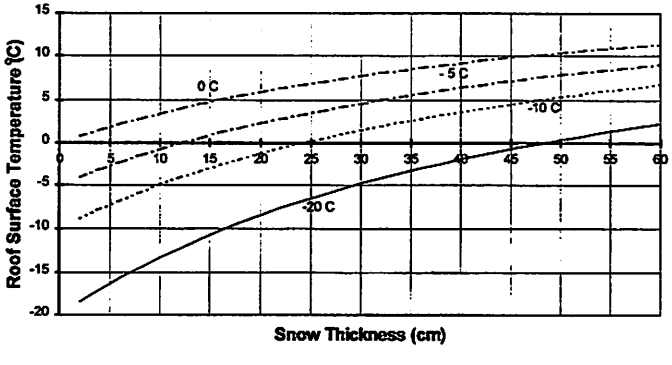

Figure 3: Estimated roof surface temperatures at various outdoor temperatures for a house with RSI 3.52 (R-20) attic insulation, as found in most older houses.

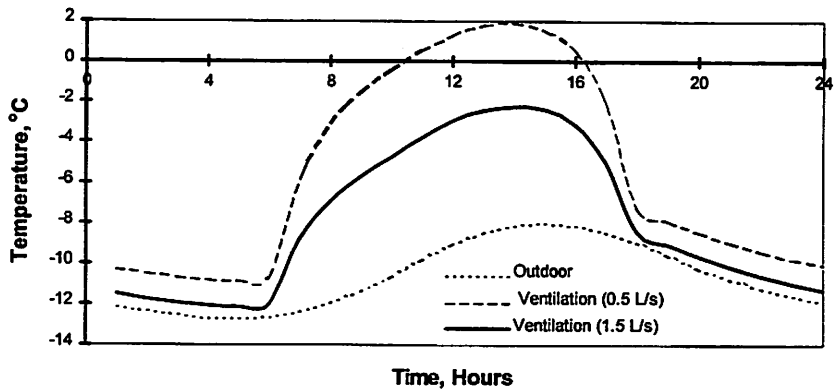

Figure 4: Effect of attic ventilation on the roof surface temperature profile on a clear sunny day. Roof is covered with 10 cm of snow.

Investigations and Findings

The field survey was conducted in the Ottawa area. The sample houses were selected by driving through new house developments and visually checking for the presence and the extent of ice dams. Subsequently, letters were dropped in mail boxes to explain the research project and to request home owners to volunteer to participate in the field study. A total of 33 houses, 16 with ice dams and 17 without, were selected. It should be noted that the main objective of the field research was to ascertain and evaluate causes for ice-dam occurrences rather than to establish the extent of ice-damming in new housing.

The following information was gathered for each sample house:

- the attic temperature and the indoor house temperature (minimum and maximum) were gathered using the indoor/outdoor thermometers;
- attic heat sources: air leakage paths, insulation type and thickness, chimney, attic hatch insulation, etc.;
- attic ventilation: type of vents, quantity, vent area (i.e., clear from insulation blockage), etc.; and
- sketches to note architectural details, location of problems, and other information.

The following sections briefly summarize findings.

Attic Temperature Analysis

The attics were monitored from late-February to mid-March 1996. Temperature readings from March 5th were used for the analysis. The weather conditions on that day were as close as

possible to conditions recognized for the occurrence of ice dams. The maximum and minimum outside temperature were -4°C and -8.7°C respectively and the mean temperature was -6.4°C. Average winds were predominantly from the East at 4.6 kilometers per hour and, there was only 2.3 hours of sunshine during the day. Figure 5 shows the minimum attic temperatures profile.

Analysis of the data showed that the average minimum attic temperatures of the ice dam houses was 3.9°C warmer than the non ice-dam house attics. The average temperature difference is even greater, at 4.8°C, if the two coolest ice-dam attics are removed from the ice-dam attic average temperature calculation.

House, Roof and Attic Characteristics

Information gathered on all 33 houses during the site visits was tabulated to identify any emerging patterns common to the troubled houses. The data was then analyzed with the following assumption being considered. For ice dams to occur, a condition must cause the snow on the roof to melt even when exterior temperatures remain below freezing. Therefore, two main factors were considered in the analysis:

- What are the heat sources that warm the attic and underside of the roof?
- How is heat removed from the attic?

A third factor considered was ice dams themselves and resulting interior water leakage:

- How does the water from the ice dam enter the attic space? (Some houses had evidence of ice dam build-up on the roof but did not have any visible interior damage reported.)

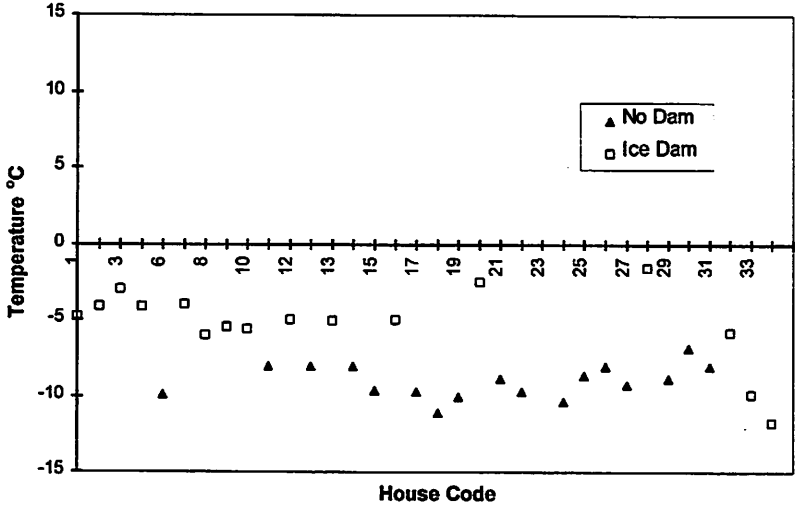

Figure 5: The minimum attic temperatures recorded for a period of 24 hours on March 5, 1996.

More than one factor can contribute to the formation of ice-dams. Various combinations of possible causes and details were considered. One main difference in the houses sampled was that the ice-dam houses were all row houses except one which was a single detached dwelling. Non-ice dam houses were all single detached houses except three which were row units. Due to the house type difference, the potential impact from party wall heat loss or attic ventilation and roof type could not be clearly isolated.

Attic Heat Sources

Information was gathered on potential heat sources that could warm the attic. The attic and hatch insulation levels were measured and point sources of heat such as chimneys, skylights, and exhaust vents through soffits were checked. It should be noted that snow covered the entire roof surface when the ice dams occurred in late 1995. This was due to the calm wind conditions which accompanied the snowfalls during the early part of the winter. Usually, parts of the roof would be cleared of snow by the wind. Solar radiation on the roof would then also contribute to increase in the attic temperature due to solar gain.

Attic Insulation

The first attic heat source considered was conduction through the ceiling and insulation. The type and thickness of insulation was checked and measured. All houses had loose blown-in attic insulation. However, some did not appear to have the required minimum settled thickness of 23.3 cm of cellulose fibre or 23.6 to 30.5 cm of loose glass fibre (depending on the manufacturer) to meet the current building code.

Specific information about the make of the glass fibre insulation for each house was not available to determine clearly if the required amounts of insulation were installed. In any case, some houses did not have enough insulation or had uneven placement of insulation which left portions under-insulated. Seven of the ice-dam houses and three of the non-ice-dam houses definitely did not meet the insulation code requirements (OBC 1993). Four more ice dam houses and three non-ice-dam houses could be under-insulated depending on the glass fibre product installed.

Almost half the number of houses which experienced ice dam problems had insulation levels about 20% lower than RSI 5.64 (R-32) as the building codes requirement applicable at the time of construction. Insufficient data was collected about insulation in contact with the roof sheathing at the exterior wall to draw conclusions about this detail. However, it was noted that there was a general reduction in insulation thickness at the exterior wall.

Attic Hatch Insulation and Weatherstripping

Most attic hatches were insulated to RSI 5.3 (R-30). However, nine houses had less than this insulation level on the hatch. Five ice dam houses had only RSI 2.6 (R-15)and one house had

RSI 3.9 (R-22). Three non ice dam cases had RSI 2.6 and two had RSI 3.9. Only two houses did not have any hatch weatherstripping. Self-adhesive foam weatherstripping was the most common type seen and only one hatch was caulked.

Chimneys

Air leakage around the chimney penetration through the top floor ceiling is a suspected heat and moisture source into the attics. Twenty-three of the houses had chimneys, either a B-vent, A-vent or both types. One main difference noted between the ice-dam and the non-ice-dam cases was the chimney location. All ice dam house chimneys pass through the top storey ceiling. The majority of the non ice dam house chimneys are located outside of the insulated exterior walls, i.e. these chimneys do not penetrate the ceiling air/vapour barrier.

Among the three non ice dam houses with interior chimneys, one had both an A-vent and a B-vent chimney (house #14), the others had B-vents only. This house (#14) had signs of moisture in the attic (frost on underside of roof sheathing). Large areas of wet roof sheathing were also observed in three of the ice dam houses with interior chimneys (houses #8, #9, #10).

Fan Exhaust Vents Through Soffits

The majority of houses had bathroom exhaust fans venting through the soffits. There were two cases where the duct from the fan was reported to be broken or disconnected under the insulation.

Other Heat Sources

Since most of the ice dam cases in the sample were row houses, it is possible that some heat transfer from the house into the attic is due to the party walls. Conduction and convection through and/or alongside concrete block party walls can account for some heat transfer into attics. However, most party wall separations in the attics were drywall clad trusses. The party wall capping at the top level ceiling in these cases may eliminate much of the conductive and convective heat loss from the house into the attic.

The single detached house with ice damming has other features which could have contributed to the problem. House #12 has a skylight and cathedral ceiling on the roof slope where water leaked in. There was visible ice build-up on the other roof slope, which has dormers and knee wall attics, but no interior damage was reported there. Reduced ventilation in a cathedral ceiling roof can also contribute to ice build up. Skylights contribute to roof snow melting, and ice dams are commonly seen below them. Air leakage could have been the heat source if a continuous air barrier was not provided from the face of the knee wall, through the floor joist space, and to the ceiling below. In addition, further complexities occur where the dormer projects out into the knee wall attic.

Attic Heat Removal

Heat can escape from attics through vents and by conduction through the roof deck and gable walls. The following presents an example of the relative contributions to heat loss by conduction through the roof deck and gable walls versus attic ventilation heat loss:

> Consider a simple gable roof house measuring 10 m by 6 m, with the gable ends along the 6 m walls. On a day like March 5, 1996, the outside temperature was -11°C and a typical attic temperature was -3°C. Under these conditions, the heat loss through the gable ends is 133 W, through the roof surface was 1530 W, and through an attic air change rate of 5 air changes per hour (ACPH) was 400 W, for a total heat loss of over 2000 W. Note that the heat loss through roof conduction is several times the heat loss by ventilation.
>
> Now cover the same roof with 20 cm of soft snow, which will also block some of the roof venting. The snow acts as roof insulation as well. The gable end heat loss remains at 133 W, but the roof loss drops to 216 W. If the attic ventilation rate drops to 2 ACPH, the attic ventilation heat loss is down to 160 W. Now the total heat loss from the attic is only about 500 W. The heat input from the house will roughly be the same in both cases. Because the attic is not losing its heat as quickly with the snow on the roof, the attic temperature will start to rise and ice damming may occur.

Information about the attic ventilation at the peak and soffits was considered to see if obvious differences existed between the warm attics and cooler ones. Peak roof vents could be blocked by snow. Soffit vents could be sometimes blocked by insulation in the attic. These blockages reduce the air movement in the attic and the effectiveness in removing heat gains.

Attic Ventilation

Attic ventilation is generally achieved through soffit vents and other types of openings at the roof peak. All houses in the survey had mushroom vents. Twelve of the 16 ice-dam houses (75%) had two mushroom vents. Three houses had three mushroom vents and one house had only one. The house with the single mushroom vent also had a turbine vent. For the non-ice-dam houses, 13 out of 17 (76%) had three or more mushroom vents. In addition to the mushroom vents, seven of the non ice dam cases had gable roofs with rake vents and/or gable vents.

Because most ice-dam houses were row units, only two cases with gable roofs had effective rake vents. There were three end units where no rake vents or gable vents were installed. The effectiveness of rake or gable vents on decorative gables was somewhat limited by the size of the

opening in the main roof sheathing. The decorative gables also tended to be lower than the peak of the main attic space and may be less effective at promoting air movement.

The number of mushroom vents on the non-ice-dam houses may reflect on the larger attic area in the sample's single-detached houses compared to the smaller row houses. In any case, it was observed that some of the mushroom vents were blocked by snow at the time ice dams occurred. The ventilation effectiveness of that type of vent would then have been reduced for all houses.

The soffit vents data was examined to determine whether these vents may have contributed to reduced ventilation in the ice dam houses. The majority of houses (88%) had 30.5 cm (12") or wider soffits vents. Few of the insulation baffles appeared to be blocked by insulation. The row houses had less overall venting area from the soffits than for the detached houses. However, there were two row houses with ice dams that had narrower soffits, only 20 cm (8") overhang. This may have been a contributing factor to the warmer attics in these two houses.

Six houses with no ice damming were noted as having more insulation baffles than other houses in the sample. In these houses, there were baffles in each truss space or double baffles between each truss. It should also be noted that one of these non ice dam houses was a row house. None of the houses with ice dam problems were noted as having lots of insulation baffles. In fact, ice dam house #16 only had 3 insulation baffles.

Architectural and Construction Details

The complexities of house and roof designs can sometime create construction details that are difficult to build. For example, discontinuities in materials at intersecting roofs, walls and valleys demand materials to perform tasks for which they were not intended. This is especially true under unusual conditions such as the winter of 1995-1996. Various notes were made about such details that could contribute to water leakage problems from ice dams.

Row houses often have staggered units to accent the facade. Some roofs then have to be flashed against the projecting exterior wall of the adjoining unit. The flashing details at the wall may not project high enough to hold back the water from ice dams at the edge of the roof. Another detail observed in the ice dam houses was adjoining unit roofs that were slightly higher or lower than the unit with interior water leakage. A minor ice dam can easily cause water to backup into the structure at such a detail.

Some units had water leakage on the main floor level ceilings and walls where the exterior wall projected out further than the second storey wall. The ice dam may have occurred on the lower level roof independently from the main roof ice dam. Some of these lower roofs also have valleys for decorative gables. Water from these lower roof valleys is sometimes directed against the exterior wall of the adjoining unit.

Decorative chimney boxes built around the A-vents and B-vents can also hinder the run-off of water from melting snow. Three ice dam cases had chimney boxes and two of these had reported water leakage close by. One particular house with ice-damming had a decorative gable adjacent to a chimney box. As a result, half of the run-off from the roof was funneled into a small area between the chimney box and the decorative gable valley.

All of the houses in the sample had roof valleys except for three non-ice-dam houses which had simple hip or gable roofs. A lot of the interior leakage problems from the ice dams were near valleys, although some leakage occurred on roof slopes with no valleys. Valleys do not cause the ice dams, but discontinuities in the sheathing, eaves protection etc., provide a leakage path for the water to penetrate into the attic when an ice dam has occurred.

Building Code Requirements

The National Building Code of Canada (NBCC) and provincial building codes require the installation of eave protection; sections 9.26.5 and 9.26.6 of the NBCC stipulate the requirements. The building codes require eave protection from the roof edge up the roof for a minimum of 900 mm (36") along the roof slope, and to extend beyond a minimum of 300 mm (12") further than the inner face of the exterior wall.

This is clearly insufficient since we have seen cases where the water leaks occur at the first joint of the plywood sheathing, which is four feet up from the edge of the roof and sometimes more than three feet inward from the inner face of the exterior wall. Furthermore, this eave protection could only be effective if it was continuous, and it is often not so at valleys, chimney boxes, and other details.

Even if done meticulously it is no guarantee that eave protection would prevent water penetrating, if there is an ice dam. In one row house development, which had been constantly plagued with ice dam problems since construction, major work was undertaken to resolve the problem. Part of the retrofit included adding an adhesive-backed eave protection membrane to the roof edge, two widths of the membrane from the roof edge up the roof. Some of these houses still had water leakage from ice dams in the winter of 1995-1996; even in some units where eave protection membrane had been installed over the entire roof area, due either to lack of supervision and/or the workers obviously not understanding the product's intent.

Building code requirements exist for attic ventilation, and if done properly to the 1:300 rule, half from the peak and the other half distributed along the eaves (soffits), it should be sufficient to prevent temperature build-up in the attic space; as long as the insulation baffles are installed and not blocked with insulation! Properly designed and installed soffit and peak vents should generate 2 to 3 air changes per hour in moderate wind conditions.

The building code also requires the ceiling plane to have a continuous air barrier. If done properly, it should not allow air leakage into the attic. This is not always the case. Problems of providing a continuous air barrier around penetrations such as chimneys seem to persist even today.

The building codes also specify insulation levels that should be installed. Some houses were found to have less than the minimum levels.

Guidelines

Based on our findings, we offer the following guidelines:

1. provide adequate attic insulation levels throughout the attic, especially where the ceiling meets the roof;
2. seal all air leakage paths from the house leading to the attic;
3. provide attic ventilation with half the vent area at the soffit and half near the roof ridge;
4. provide insulation baffles in every truss space, especially in row houses where there is less linear footage of soffit venting compared to detached houses, and ensure that these baffles are not blocked with insulation;
5. during the re-shingling of existing houses or installing shingles in new houses: install an eave protection membrane extending beyond the code requirements (from 0.9 m to about 2 m); and install an impervious roofing strip in valley intersections;
6. in new construction: use high heel trusses; insulate to the outside of the top plates; and install insulation baffles to ensure ventilation at eaves; and
7. in new construction or retrofits: avoid architectural features that force water and melt-snow to concentrate on certain areas of the roof, such as multiple dormers or false gables and skylights.

Summary and Conclusions

Analysis of the data showed that there are combination of factors which affect the formation of ice-dams under given conditions. There were clear indications that warmer attics were prone to ice-dam problems. Heat losses into the attic raises the roof surface temperature significantly. Following is a summary of findings:

- The ice dam house attics were about 4°C warmer than the non ice dam house attics.
- Attic insulation levels were about 20% less than the building code minimum required RSI level in seven houses with ice dam problems and in four non ice dam houses.
- Attic hatch insulation levels were significantly lower in five ice dam houses (RSI 2.6 or R-15), while non ice dam houses had attic hatch insulation of at least RSI 5.2 or more.

- Air leakage at a chimney penetration into the attic is a suspected major source of heat transfer. Most ice-dam houses had interior chimneys and non-ice-dam houses had exterior chimneys.
- Inadequate soffit venting seems to be part of the problem for warmer attics. Some ice-dam houses had fewer insulation baffles installed compared to the non ice dam cases. Limited soffit vent area in two cases (roof overhang was only 20 cm) may be a factor contributing to the problem.
- Some house designs and details may have contributed to the ice damming problem and permitted water leakage from the ice dam into the structure.
- Guidelines are suggested to help and to ensure good attic ventilation, especially better air movement, and thus reducing the heat build-up in attics. This will help to prevent problems of water leaks due to ice-dams.
- Additional on site investigations are required to confirm suspected heat sources and to verify restricted attic ventilation. Items to be verified would include: air leakage points at party walls, chimney penetrations, and underside of knee wall; connections and continuity of bathroom exhaust fan ducting through attic and to the exterior; blockage of insulation baffles, and so on.
- The study emphasizes the need for proper levels of attic insulation, air-sealing of attic penetrations, adequate ventilation of attic spaces and proper detailing of roofing at valleys, chimney boxes and edges for prevention of ice-dam related problems.

Acknowledgment

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Towards Integration of Service Life and Asset Management Tools for Building Envelope Systems

M. A. Lacasse[1], D. J. Vanier[1], B. R. Kyle[2]

Abstract

Asset managers are faced with many difficult decisions regarding when and how to repair their building stock. The reasons for the difficulties relate directly to the lack of usable data, information and knowledge related to service life prediction, and the lack of tools to assist the asset manager in making a proper repair choice. The Building Envelope Life Cycle Asset Management (BELCAM) project addresses these two deficiencies: its goal is to develop methods to predict the service life of the building envelope and its elements, and to assist asset managers in maintaining these building components. The project in the initial stages focuses on roofing, and seeks to integrate existing enabling technologies used in this domain, namely: maintenance management, life cycle economics, service life prediction, user requirement modeling, risk analysis, and product modeling. Although there exists degradation models for flat roof systems, as well as a number of roofing maintenance management packages, these have yet to be integrated into a consistent resource that satisfies the asset manager's requirements. Indeed, efforts have been made in the past to provide designers insight into the functional use and related performance requirements of building elements; however, little of this information has been used in the context of maintenance of facilities. This paper describes details on the programmed approach adopted within the BELCAM project to achieve practical solutions for asset managers. Examples are provided to illustrate the concept as applied to the roofing domain.

Keywords: Asset Management, Building Envelope, Durability, Information Technology, Life Cycle Costs, Maintenance Management, Risk Analysis, Service Life Prediction, Product Modeling.

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Introduction

Asset managers are faced with many difficult decisions regarding when and how to repair their building stock. The reasons for the difficulties relate directly to the lack of usable data, information and knowledge related to service life prediction, and the lack of tools to assist the asset manager in making a proper maintenance, repair or replacement choices [1,2]. Some of the most difficult decisions relate to the building envelope, which normally incurs the major portion of the initial cost of a building and it is the most significant system in terms of maintenance, repair and replacement [3].

It may be generally acknowledged that building construction expenditures in Canada represents a significant portion of the total value of construction. Indeed, a review of construction statistics [4] has shown that every year, between 1983 and 1993, 52 billion dollars, on average, was spent on building construction, representing about 65 percent of the total value of construction in Canada. Maintenance and repair expenditures are no less significant; a review of the proportion of repair expenditures in relation to total construction expenditures in this same period revealed that yearly, roughly 16 percent, on average, is spent on repairs representing a value of 8.5 billion dollars for repairs to building construction alone. Of this value, maintenance repairs to roofing membranes and systems may account for approximately 30-35 percent of these costs or approximately 2.5-3 billion dollars. In the United States of America the numbers can be conservatively estimated at ten times higher [5]. Therefore, asset managers are responsible for managing a substantial amount of construction and maintenance work. In many instances, the initial design and construction costs are small compared to the asset maintenance costs throughout the building's life: this makes the asset manager a major player in the construction game.

Asset managers are faced with many difficult decisions regarding when and how to maintain and repair their constructed facilities. The reasons behind these difficult decisions are the growing fiscal constraints, an increasing maintenance deficit and a substantial repair backlog. In addition, asset managers resources are being challenged from all sides: they are also being asked to cut cost, to privatize operations, to outsource responsibilities, to reduce maintenance and to increase efficiency. These problems are exacerbated by the lack of usable data, information and knowledge related to maintenance and repair, and the lack of tools to assist the asset manager to make proper inspection, maintenance and repair choices.

Many of these problems would be solved if there was more information exchange in the construction industry regarding service life and asset management. The roofing industry is no different from the rest of the construction sector: money is tight, maintenance backlogs are increasing and information is scarce.

Many organizations have recognized the asset management problems identified in the previous section [5-7]. Unfortunately existing opportunities offer only partial solutions to many of the problems in asset management, and more specifically to the problems in roofing asset management. There is still need for research in this field: (1) what data should be collected, (2) what are the life cycle costs of maintenance, (3) what data are required for service life prediction, (4) what is the essential maintenance and what can be deferred, (5) how to deal with risk and the consequences of asset failure, repair and renewal, and finally, (6) how to integrate all these new data and information.

The NRCC and PWGSC are addressing these questions with the BELCAM Project. The BELCAM project will attempt to build on the existing service life and asset management information discussed above, will endeavour to provide a clearinghouse for service life and asset management research for roofing systems, and will provide tools and techniques for building practitioners.

BELCAM Approach to Roofing Asset Management

The overall goals of this initiative are:

1. To develop models and tools to facilitate predicting the service life of building components.
2. Assist asset managers to maximize the effectiveness of their maintenance dollars.

The objective of this initiative is to develop models, methods and tools to achieve these goals. This joint NRCC/PWGSC initiative should be considered as the large picture on service life and asset management research; however, to meet the goals and objectives there is need for focused research and development in specific construction sectors. NRCC and PWGSC have agreed to participate in a pilot project dealing with near-flat roofing systems.

Service Life / Asset Management Enabling Technologies

The BELCAM project [1,2] has identified the six enabling technologies, illustrated in Figure 1, that can help asset managers predict the service life of building envelope components:

- Maintenance Management to record and monitor the current condition of building elements and systems;
- Life Cycle Economics to model the construction as well as operation and maintenance costs from cradle to grave;
- Service Life Prediction to collect the necessary laboratory and field data for the development of building component performance curves;
- User Requirement Models to quantify the desired building performance levels and to establish criteria for;
- Risk Analysis to determine the probability and consequences of repair and rehabilitation decisions;
- Product Modeling to manage and integrate data and information related to service life prediction and asset management.

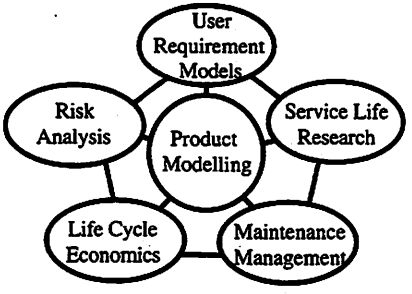

Figure 1: BELCAM Integrated Models

In essence, the six enabling technologies address many of the problems identified in the previous sections, as well as, many of the objectives for sustainable roofing. That is, the integrated model shown in Figure 1 identifies the need for close ties between maintenance management, life cycle economics, and user requirement models; these are all components of a sustainable roof system. Product modeling is seen as the integrator for these well-established research areas.

Enabling Technologies: a synopsis of the current State-of-the-Art

User Requirement Models

User requirements and their relationship to functional requirements for building elements have been derived from work on the performance concept in building technology. Although a proposed structure for the performance concept has been available for more than two decades [8], there has since been considerable research in this field, much of which has evolved within the CIB Working Commission on the Performance Concept in Building [9,10]. The definition of the performance concept "takes as a starting point a recognition of the needs expressed in terms of human and user's requirements". This CIB Working Commission also supplements the earlier work in the field with clear definitions for terms such as "stress", "functional performance requirement", and "performance assessment". CIB W60 has worked to provide more depth to the vocabulary and structure and has promoted the development of performance standards. Indeed, the building industry now has concise descriptions of the performance concept included in ISO documents that provide clear and concise examples and classifications for components of the performance models. A number of formats and templates for the development of performance standards [11-13] are available and this work has been applied in a number of domains [13].

Within the roofing industry, attempts are being made to establish a consistent set of performance standards related to building functional requirements: work has been undertaken to describe and relate the functions and components [14] and to outline the performance requirements in terms of specific test standards and specifications [15]. Although there appears to be a certain degree of skepticism in regards to the use of the performance approach to meet industry needs [16,17] there nonetheless is a recognition that new methods are needed to interrelate functional requirements to performance requirements, and specifications [18].

The BELCAM project is developing a user requirement model for the roofing domain called FRAME (Functional Requirement Analysis and Modeling Environment) [19]. It is expected that the user requirement model will be applied in two modes: the functional programming stage of the design process, and, in performance assessment. In the functional programming stage FRAME will find solutions in a multi-variant decision process. The assessment service includes, in the first instance, the commissioning phase of the construction process, where the completed structure is evaluated for compliance to functional building requirements. The assessment service would also include post-occupancy data collection and performance evaluation for the maintenance, repair and rehabilitation phases. Basically, for the applications identified above FRAME can be used to: (1) select the Occupancy (Use); (2) select the appropriate Functional Requirements, taking into account the Occupancy (Use); (3) select suitable Functional Elements to address the Functional Requirements, taking into consideration the applicable Agent (Stress); (4) select the desired Performance Requirements, taking into account the Occupancy (Use); (5) select the appropriate Performance Indicators, taking into account existing standards and testing procedures; (6) establish the Performance Indicators, as well as the Nature and Criteria for assessment, and (7) evaluate the performance. These technical terms are illustrated in Figure 2, below.

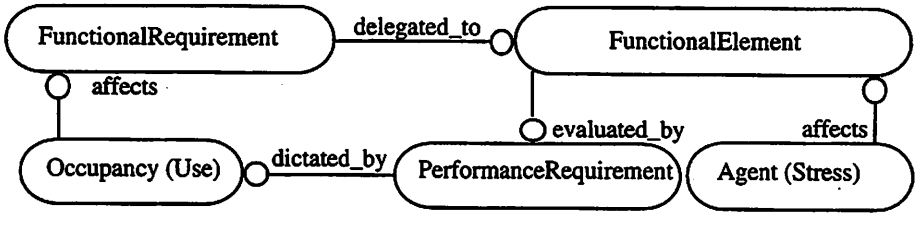

Figure 2 FRAME Product Model [19]

Service Life Prediction

The body of knowledge encompassing the durability of building materials is evidently quite large and this is also true for the roofing domain [2]. Numerous studies have been undertaken to report on the durability of specific roof types, components, or materials in particular those elements of the roofing system identified as having failed prematurely [20]. Studies have, hence, been conducted on understanding premature failure phenomena, causes and prevention. For example, a more recent focus has been on the performance of roofing membranes, in particular single-ply EPDM membranes and those made of un-reinforced PVC. More specifically, in the case of EPDM membranes [21], the effects of shrinkage were found to be the primary factor in the premature failure of these systems, whereas, in the case of PVC membranes [22], considerable research has been undertaken to determine the causes of shattering on these roofing components.

Statistical methods have been used to evaluate the long-term performance of roofing systems[23]; however, few comprehensive methods combining field studies, laboratory accelerated test methods and modeling have been developed. In this area, Baskaran and Paroli [24, 25] are providing insight towards developing a comprehensive evaluation program for roofing membranes. This approach is based on an understanding of the most significant factors causing degradation of low-slope roofing systems and encompasses the use of a dynamic wind test facility together with modeling expertise. In is anticipated that the research results from this work will be incorporated in the BELCAM service life model.

Roofing literature related specifically to predicting the service life of roofing systems is limited not only in terms of scope but also in terms of relating results to in-service conditions. Within the service life area, an attempt will be made to determine what literature is relevant to the domain, to highlight the most significant studies in the area, to review the techniques used and to develop a common vocabulary related to roofing service life. Research undertaken by others in this domain will be incorporated into the service life model.

Risk Analysis and Reliability Assessment

The reliability-based approach is often utilized in assessing the long-term performance of various types of structures or materials [26,27]. It is based on two concepts, the first of which is related

to the loss in performance with time (P_t) of a product, or built system, when subjected to a series of loads (including environmental as well as structural) causing deterioration (S_t). The second concept defines failure which arises when the level of performance of the system can no longer sustain the loads to which it is subjected. In other words, failure occurs when $S_t \geq P_t$. The margin of safety of a given system is simply the difference between P_t and S_t at any time, t, and, as a system degrades in time, its margin of safety is reduced. Risk and reliability are two related terms in which risk represents the probability of failure of a given system in a given period of time, and, reliability is the probability that this same system will survive (*i.e.*, not fail). What is important in systems that are to perform in difficult environmental conditions over extended periods of time is maintaining the reliability of these systems, not their condition. Thus, data collected in a condition survey should reflect the change in the reliability of the system as a whole. This implies that the state of condition of a system being inspected should then be linked to the change in reliability of the system or its components. In this way, programmed maintenance and repair for a given system can be based on updated reliability estimates. These techniques represent a valuable tool for maintenance managers to minimize their maintenance costs and maximize the value of their assets.

This method is gaining acceptance in areas such as concrete bridge maintenance and repair strategies, and has been successfully applied to assessing the long-term performance of parking garage structures and to determine the probability and consequences of repair and rehabilitation decisions [28,29].

In the area of roofing, the reliability-based approach was first suggested by Masters [30]. Thereafter, Martin et al. [31] applied these methods of analysis to determining the service life of adhesively bonded seams of single-ply, EPDM, roofing membranes. More recently, Kyle [32] together with Marcellus and Kalinger [33] have shown that a similar approach, based on a statistical analysis of roofing defects over time, can be adapted to resolving maintenance and repair issues related to low slope roofs. The proposed reliability based system being developed by PWGSC will help make maintenance management decisions based on structured data.

Within BELCAM, the risk analysis and reliability assessment model will be used a basis for formulating different inspection, repair and rehabilitation strategies and the development of cost minimization functions.

Life Cycle Economics

In the engineering domain, life cycle costing has been typically used to assess the economic feasibility and benefits of different design or retrofit options. The methods are well documented in a number of [34] and are increasingly being used in the roofing area to assess when to repair or retrofit, or in the selection of new roofing systems [35]. Fundamental components of an analysis include: unit costs to replace, repair, inspect and maintain the roof, as well as design service life and anticipated frequency of inspection and routine maintenance.

The importance of roof inspection and maintenance costs should not be overlooked; studies undertaken by the maintenance division of the department of the US Air Force have shown that aggressive maintenance can provide savings ranging between $1.50 and $2.45 per square metre ($0.10 and $0.15 US per square foot) over moderate inspection. Aggressive maintenance means a semi-annual inspection that includes an annual moisture survey whereas conventional implies a walk-around annual inspection [36]. Level of investment (LOI) studies [5,6] have indicated that maintenance expenditures should be between two and four percent of the capital replacement value (CRV) of a facility. Although CRV has yet to be rigorously investigated for different types of facilities, it nonetheless provides a good basis from which cost estimates can be made. A number of ways have been proposed to determine the CRV; it may be based on: the purchase price plus an appreciation factor, a current cost to replace the asset, or, the cost to replace the functional portion of the asset with current construction technology. However, there are other elements that must also be considered when planning over the life of the facility, including renewal of the roof at the end of its service life.

In this regards, The National Association of College and University Business Officers [6] has proposed a detailed process consisting of identifying work that is capital renewal from that which is deferred maintenance. In this process, the asset manager first identifies maintenance that has been postponed, phased or deferred, and then attempts to provide an estimate of the cost for that deferred maintenance. The second portion of the process is capital renewal (CR) analysis in

which the replacements that will be required at the end of the service life of various parts, components or systems are likewise identified. The CR process also includes estimating the renewal costs in five year lumps, and spreads these costs equally over each year. In this way, costs for CR for each system type can be calculated well into the future, and can be brought forward to a present value or calculated as an annuity expense. This process can readily be applied to the roofing industry.

Maintenance Management

In North America, the importance of roof management programs is well understood in both the private [37,38] and public sectors [39]. Both sectors have made a point of providing the necessary guidelines for inspection and maintenance of roof systems [40-41]. Hence, there is considerable literature available in this area from which a standard and systematic approach to roofing maintenance management can readily be developed. Moreover, there now exists a number of computerized maintenance management systems (CMMS), however, their usefulness with respect to life cycle economics and maintenance management is less well known. Many of these are relational database applications that have been developed to meet the data handling needs of asset managers. For example, any number of database applications can manage work orders, trouble calls, equipment cribs, stores inventory, and preventive maintenance schedules, and many include features such as time recording, inventory control and invoicing.

The Construction Engineering Research Laboratory (CERL) has pioneered the use of engineered management systems in many construction sectors including roofing, paving and rail networks [42-45]. Engineered management systems (EMS) attempt to establish a condition index (CI) of an asset based on a number of factors including the number of defects, physical condition and quality of materials or workmanship. Research studies have estimated the potential degradation of the CI based on loads on the system or external agents acting on materials. With all these data in hand, it is therefore possible to estimate the CI well into the future, given degradation curves and the effect of remedial action.

A number of commercial packages exist in the roofing domain of which MicroROOFER, developed by CERL, deals with three CI including the Flashing Condition Index, Insulation Condition Index, and Membrane Condition Index.

Product Modeling

As stated earlier, it is envisaged that product modeling will be used to manage and integrate data and information related to service life prediction and asset management [46]. Product modeling is a means of expressing notional concepts describing different 'products' and their interrelationships in a 'computer-interpretable' format. ISO 10303 is the international standard for the "computer-interpretable representation and exchange of product data" [47]. EXPRESS is its specifications language that provides the necessary language elements for an unambiguous definition of concepts. Text-based representations such as EXPRESS are easily understood by computers, but are difficult for humans. Graphical notations, such as EXPRESS-G, have been successfully developed to represent the complex relations typical of construction components and materials [48]. Based on the general acceptance of EXPRESS-G by the construction product modelers, it was selected to model the BELCAM user requirements. Hence, this tool will be used to derive a product model specific to the roofing domain that will encompass all of the pertinent enabling technologies briefly described above.

Summary and Future Work

In summary, asset managers face many difficult tasks to maintain their building stock in the existing economic times, but fortunately, there are many opportunities to assist them with their problems. However, to take advantage of these opportunities requires a concerted effort from the following three construction communities: research, standards and practice. In essence, without standards there is marginal service life information exchange to practitioners and without research there is limited information and data for development of useful standards.

The technological solutions to the problems of deferred maintenance and expensive capital renewal are neither imminent nor obvious. However, the problem is not intractable provided asset managers have a comprehensive suite of tools to help them manage their facilities. The BELCAM project attempts to address such problems in roofing asset management. The enabling technologies briefly described in this paper provide the research framework for developing tools to collect, classify and analyse service life and asset management data. Provided below are brief descriptions of the types of products the project will deliver in the coming three years.

The deliverables of the three-year BELCAM Project are as follows ('W3' indicates that the deliverable will be available on the World Wide Web):

1. Planned Deliverables (Year One)
   - Roofing 'Standards' Database: A database of Canadian standards on roofing including references to Canadian Construction Codes, Canadian Government Specifications Board (CGSB), and Canadian Standards Association (CSA), including CSA S478 "Guideline on Durability in Buildings" (W3).
   - Roofing Checklists: Inspection sheets based on best-practices, guidelines, or manufacturer's instructions available electronically (W3).
   - Roofing Software Evaluation and Analysis Report: An up-to-date evaluation of software for the roofing industry, including an analysis of ROOFER (W3).
   - Roofing Resources: Technical and practitioner publications (W3).
   - Roofing on the Internet: An analysis of existing Internet web sites dealing with roofing issues (W3)
2. Planned Deliverables (Year Two)
   - Roofing Inspection Manual: A manual of when and how to inspect a roof (W3).
   - Preventive Maintenance Checklists: Inspection reports made available through the Internet to maintain roofing inspection data (W3).
   - Regional Roofing Survey: A comprehensive survey of roofing in the Ottawa region to establish data for service life research.
   - Roofing 'Standards' Expert System: An expert system to indicate which standards are applicable for a specific roofing design.
   - Roofing Costing Data: Information on repair costs that are based on the Regional Roofing Survey and other costing sources of repair data (W3).
   - Roofing CAD Details: Standard CAD details for recommended repairs (W3).
   - Roofing Defects Database: A database of defect, including graphics, and remedial action (W3).
3. Planned Deliverables (Year Three)
   - Roofing Risk Index: A method for assessing the risks and potential costs of repair, based on age of roof, maintenance profile, defects and roof condition.
   - Roofing Condition Expert System: An expert system to predict the service life of roofing systems, based on inspection, maintenance profile and defects (W3).

- Roofing BELCAM Database: An object-oriented database management system for inspection, maintenance, repair and renewal of roofing systems (W3)
- Roofing Maintenance Software: A software package (such as ROOFER), developed or modified to suit BELCAM user requirements, for roofing maintenance (W3).
- Guideline on Roofing Service Life and Asset Management: An objective-based guideline for ensuring that roofing system are "designed for service life".

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Guideline on Durability in Buildings: Development, Content and Implementation of CSA S478

G. Adaire Chown and John Vlooswyk*

Abstract

Public Works and Government Services Canada (PWGSC), because of a concern with the high cost of repairs caused by premature deterioration of their building stock, was one of the first of Canada's major building owners to recognize the need to address building durability issues in an explicit, detailed and comprehensive manner. To this end, PWGSC initiated, supported and provided input into the Canadian Standards Association document CSA S478, "Guideline on Durability in Buildings".

The present paper describes the development of CSA S478 and summarizes the information provided in the Guideline including: intent and scope; specification of design service life; the correlation between component service life and building service life; methods to predict actual service life; and durability considerations through the various phases of the building life cycle including design, construction, operation, maintenance, inspection and renovation. The importance of quality assurance is highlighted and the concept of performance assurance is introduced. The paper describes how the guide may be used, and introduces the structure that is provided for recording critical information and decisions pertaining to design life and maintenance.

A number of comparisons are made with the related British and Japanese documents and with the draft ISO standard, and suggestions are made for future development of the CSA guideline.

Since its release, the Guideline has been used by various public and private sector agencies. Information is provided on the on-going implementation of the guideline and the barriers that preclude more rapid and wide-spread adoption.

Keywords

building envelope, buildings, design service life, deterioration durability, failure, guidelines, performance assurance, predicted service life, quality assurance, service life, standards

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Guideline on Durability in Buildings: Development, Content and Implementation of CSA S478

G. Adaire Chown and John Vlooswyk

Guideline development

Public Works and Government Services Canada (PWGSC), concerned with the high cost of repairs related to premature deterioration, was one of the first of Canada's major building owners to recognize the need to address building durability in an explicit, detailed and comprehensive manner. As part of its durability program, PWGSC initiated, supported and provided input into the development of the Canadian Standards Association (CSA) document CSA S478, "Guideline on Durability in Buildings" (CSA guide) [1].

The CSA guide reflects the consensus of a broad range of industry interests: from the regulatory expertise of municipalities and the Canadian Codes Centre, Institute for Research in Construction (IRC), National Research Council (NRC); through the practical experience of building owners, materials producers and design, construction and consulting firms; to the research expertise of universities and IRC/NRC.

Early work on the CSA guide drew heavily from the British document BS 7543 "Guide to Durability of building elements, products, and components" (BSI guide) [2]. The CSA guide evolved, however, to be significantly different in scope and focus, and to have greater breadth and depth. Though a copy of the Japanese publication "Principal Guide for Service Life Planning of Buildings" (AIJ guide) [3] was not obtained until the CSA guide was essentially complete, there are significant similarities between these two documents. The AIJ guide, however, appears to have involved significant literature review while the CSA guide relied essentially on the collective knowledge and expertise of the committee members; few resources were available for additional research.

Scope, content and structure

The CSA guide largely reflects the priorities of PWGSC and perceptions of major avoidable costs that arise over a building's life. Consequently, the guide focuses on durability of structural and building envelope elements. Building services were not specifically addressed in the development of the guide though much of the information is equally applicable to these systems.

The contents of the CSA guide may be divided into four subject areas: basic durability and service life issues; addressing durability through the building life cycle; recording and communicating durability related decisions; and supporting information on loads, deterioration mechanisms and responses.

Basic durability requirements and service life issues

Basic requirements

The CSA guide states that, to ensure durability, buildings and their materials, components, assemblies and systems must be "designed, constructed, operated and maintained in such a way that, under foreseeable environmental conditions, they maintain their required performance over their design service lives", and that these design service lives must be less than the related predicted service lives. This statement is consistent with other basic durability requirements provided in the literature.

Service life

The CSA guide defines service life as "the actual period of time during which the building or any of its components performs without unforeseen costs or disruption for maintenance and repair". The term "unforeseen" is problematic and might better be replaced by "major". That is, costs for major retrofit, replacement or renovation, which may well be foreseen, can define the end of service life if they exceed a certain level. Where cost is less than this limit, maintenance, repair or replacement, whether foreseen or not, will not generally define the end of service life. (See Example and figure 1.)

Example:

A light fixture is required to provide a certain minimum light level.

Due to dust deposited on the lamp, reflector or lens, the fixture may over time fail to provide this light level. As performance falls below the limit state, the fixture in effect fails to perform as required but service life has not ended. Minimum expenditure is required to clean the fixture and reinstate performance.

When the lamp in the fixture burns out, the lamp itself has reached the end of its service life but the light fixture has not. The lamp may be replaced for reasonable cost and the unit continues to function.

Obsolescence or physical damage may require a major expenditure of resources to re-establish performance. At this point, the end of service life has been reached. If the resources are expended to repair or replace the fixture, it would acquire a new service life.

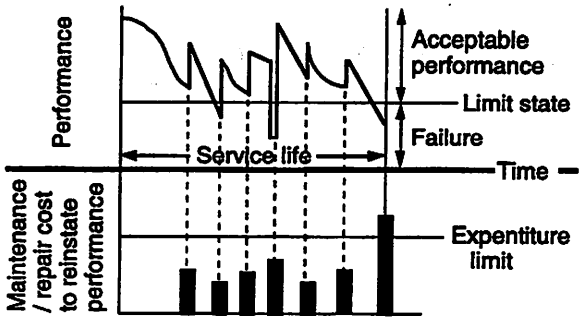

Figure 1: Service life related to performance and cost to maintain performance

The CSA guide may be unique in that it addresses explicitly the review of design service life when a building, system, assembly or component undergoes major renovation, repair or replacement. After a major expenditure of resources, the building or building element would have a new lease on life and a new design service life would be assigned. The new design service life may be quite different from the previous service life.

The CSA guide identifies four failure limit states – collapse, local damage, displacement and discolouration – all of which are related to physical deterioration affecting safety, loss of function of the building or building element, or appearance. Referring to figure 1, performance:time curves for a building element could be developed for each of these four limit states. Should any of the curves fall below the limit state for that curve and the cost to reinstate performance exceeded the expenditure limit, service life will end.

The issue of obsolescence as a limit state is mentioned in a couple of instances but discussed only briefly. To address durability and service life in a comprehensive manner, both economic and functional obsolescence should be considered.

For comparison, the AIJ guide defines the limit of service life as the lesser of the periods to reach physical deterioration, degradation of performance or economic or functional obsolescence. These states would be considered to be reached when, for a building, "large scale renovation, reconstruction or demolition" is required, or for components, when "large scale repair, replacement or renewal" is needed. "Large scale" is, of course, a relative term but the intent is clear.

Design service life

Design service life is the service life that the building owner wishes to achieve or, after consultation with the designer, agrees will be adequate. The designer uses this value to select or design building elements and materials. Before final agreement is reached on the design service life for any material, component, assembly, system or the building as a whole, it may be subject to revision depending on the initial cost, or the operation and maintenance costs of achieving that life.

Building design service life

The CSA, BSI and AIJ guides provide tables of classes and years to assist in the categorization of building design service life. The CSA guide reflects the approach taken in the BSI guide, defining five categories with examples of building occupancies that would probably fall within each category. (Table 2 in the CSA Guide is missing the line for "short life" buildings, such as temporary classrooms, which would be expected to have design service lives of 11 to 24 years.) The AIJ guide defines nine categories and its commentary describes alternative breakdowns.

The AIJ guide provides recommended building design service life periods related to both occupancy and structural material, and recommends longer building service lives to optimize life cycle cost and to comply with social requirements such as efficient use of resources. The BSI and CSA guides, addressing only durability to the exclusion of other life cycle issues, reflect typical practice of many North American speculative building developers who effectively specify short design service lives even where the more durable building elements would be cost effective over the building's life.

Component design service life

In the BSI guide, a table is provided of component design service lives; three categories are identified based on whether the building element will last for the building design service life with or without maintenance. There is also a discussion of the relationship between component design service life and implications of component failure.

The CSA committee felt that component design service lives should not be related simply to the need for maintenance or replacement over the design service life of the building, but should also indicate the frequency of, and cost and level of effort required for maintenance, repair or replacement of the component. A detailed table of structural and building envelope elements was compiled relating, for sample building types, the component design service life to the building design service life, and to the cost and complexity of maintenance, repair and replacement (see Table 1). There was some concern, however, that the example design service life figures in the table might be taken as recommended rather than example values. In the event, the table was omitted from the published version of the guide but the various relationship issues are discussed.

Similar to the approach taken in the CSA guide, the AIJ guide recommends design service life ranges for a number of structural, envelope and service components depending not only on building design service life, but also on the type of element and the difficulty of replacement. The AIJ guide also recommends the selection of building elements with similar design service lives to allow coordination of maintenance, repair and replacement.

			E.g. 1: Temporary classroom to be moved every 5 years			E.g. 2: Office Building		
Building Design		Category	*short life*			*long life*		
Service Life		Period	*15*			*60*		
resources to maintain performance relative to building design service life			major	significant	little or none	major	significant	little or none
Structure								
	foundation –	footings		*5*				*75*
		foundation walls						*75*
		slabs on ground						*75*
	typical storey -	beams, joists			*50*			*75*
		columns, studs			*50*			*75*
		slabs, decks			*50*			*75*
Environmental Separator								
	walls -	cladding			*50*	*30*		
		flashing			*50*	*50*		
		sealants		*5*		*5*		
interior:		insulation			*50*	*50*		
exterior		air barrier membrane			*30*	*30*		
above		vapour barrier			*50*	*50*		
ground		back-up			*50*	*50*		
		fastenings			*50*	*30*		
	roofs -	roofing			*20*	*20*		
		flashing			*20*	*20*		
		fastenings, ballast				*20*		
interior:	walls -	framing			*15*	*10*		
interior		drywall			*15*	*10*		
Finishings, Furnishings, Fixtures								
	painted surfaces			*3*			*1 - 10*	
	carpet			*5*			*5 - 10*	
	hard flooring				*50*			*75*

Table 1: Excerpt of table showing example component design service lives related to building service life and cost, frequency and difficulty of maintaining performance

Notes: Design service lives are agreed upon by the designer and the owner. Where a component design service life is shorter than the building design service life, the maintenance category will be "significant" or "major" depending on difficulty, expense, and frequency of replacement of that component.

The governing criteria for selection of design service lives and maintenance categories should be identified; that is, whether the termination of service life relates to one of the categories of failure (see Table 3 in the CSA guide), to failure of another component, or to expected changes in building use. Component maintenance categories should also recognize the potential for and implications of premature failure.

Predicted service life

To achieve an acceptable degree of durability, the predicted service life for the building and each of its components must exceed the respective design service lives based on reliable prediction methods.

The CSA guide identifies three methods to predict service life: demonstrated effectiveness, modeling of the deterioration process, and testing. The guide indicates when each method is appropriate and when more than one method should be used.

The BSI guide identifies three methods of predicting service life based on physical deterioration: previous experience, extrapolation of measured deterioration over a short period, and interpolation from accelerated tests. Because predictive methods are imprecise, it is recommended that more than one approach be used and the results compared. However, no information is provided to indicate where one method might be preferable over another.

The AIJ guide provides the most information on prediction of service life. It outlines a procedure for predicting service life limited by physical deterioration and references a number of methods developed internationally. Example tables of priority ratings related to performance requirements (loads) and use of buildings, spaces and elements are included. The AIJ guide also provides detailed information on calculation methods for predicting service lives of various materials based on physical deterioration. These are strongly empirical, however, and rely heavily on records of past performance. Information is provided on means to "prevent" obsolescence but not methods to predict time to failure due to obsolescence.

The draft ISO standard "Planning of, and Management for, Buildings: Service Life Design" [4] also presents a calculation method referred to as the factorial coefficient method. Using this method, a standard service life is multiplied by a range of factors to produce an estimated service life for a particular installation. The factors included in the equation are: performance of materials, design level, work execution level, indoor environment conditions, outdoor environment conditions, in-use conditions and maintenance. The difficulty with implementing this approach is in determining the appropriate values to be used for the standard service life and for each factor.

Durability through the building life cycle

People and process

To ensure that durability is maintained above the minimum required level and that building elements achieve their design service lives, durability must be addressed at each and every stage of the building's life. In this regard, information provided in the CSA and AIJ guides are the most comprehensive (see figure 2.)

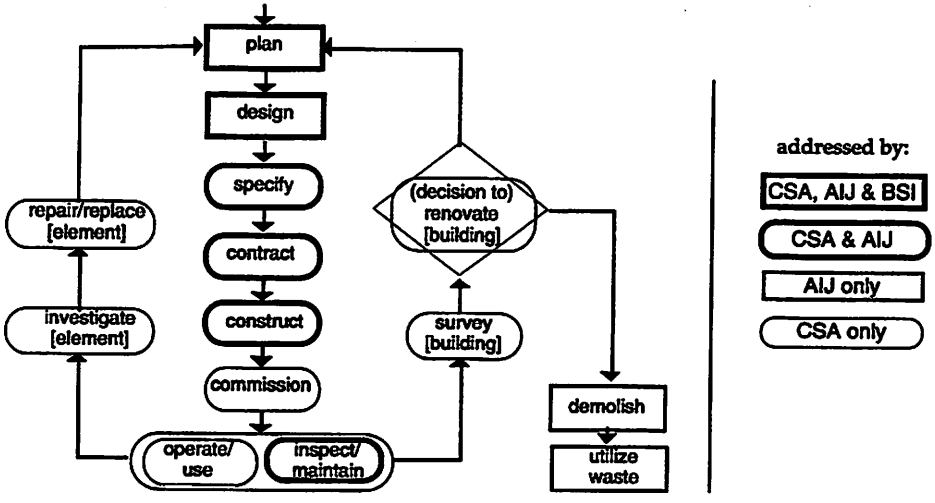

Figure 2: Life cycle stages addressed by the durability / service life guides

All of the guides identify a number of participants in the building life cycle; for example, the owner or client, designer, supervisor, constructor, operator or caretaker, and occupant or user. In some cases, responsibilities for certain actions or decisions are assigned to specific participants. Because the CSA and AIJ guides address more stages than the BSI guide, they also provide more information on the roles of the various parties throughout the building life cycle.

Quality assurance, performance assurance and durability

Quality assurance (QA) as critical to ensuring durability. QA is comprised of "all those planned and systematic actions needed to confirm that products ... will satisfy specified requirements" [1]. The QA program provides a structure for the process to ensure that durability issues will be addressed. Putting quality management into practice through the building life cycle is consistent with the direction taken in the CSA and AIJ guides of identifying the need for various participants to assume responsibility for specific decisions and tasks.

Performance assurance (PA) encompasses the QA actions that are carried out from the design stage up to and including handover, and that specifically address the performance of the product. It incorporates the definition of the criteria against which product performance is assessed and the methods used for assessment (see Figure 3).

Commissioning is one PA activity that may be used for some building elements to assure their performance at the time of completion. For other elements, such as the building envelope, commissioning on its own may provide inconclusive information on the cause of inadequate performance. Furthermore, the costs of rectifying building envelope problems after installation of the elements are often exorbitant. In these cases, executing the complete range of PA actions provides the best means to ensure that performance requirements, including durability requirements, will be met.

Stage in Building Life Cycle	Quality Assurance Activities	
Conception	• establish appropriate levels of performance for building and components	Performance Assurance
Design		• prescribe performance criteria for materials, components and assemblies • confirm acceptability and achievability of performance • specify test options (mock-ups, in situ, etc.)
Tendering	• review design documents, including performance specifications • accept requirements (contractor) • accept tender(s) (owner)	
Construction		• control through - review of process and product - sampling and testing - correction of deficiencies - certification of work according to compliance tests specified in the design documentation
Handover		• commissioning - verification of performance of completed building by testing under operational loads
Operation & Maintenance	• operate within paramenters • monitor performance • maintain according to maintenance program • inspect for deterioration or distress • investigate problems • repair/replace following Conception through Handover steps above	
Renovation	• follow Conception through Handover steps above	

Figure 3: Building life cycle stages indicating QA and PA activities (based on CSA guide Table 1)

Planning/conception

At the planning stage, building use is defined, structural and environmental loads are identified, preliminary decisions are made related to materials, components and assemblies to be used, and initial building and component design service lives are established. Tables A-1 "Building Design Data" and A-2 "Preliminary Design and Maintenance Options" in Appendix A of the CSA Guide provide a structure for recording this information (see Table 2). The information recorded in Table A-1 is intended to provide a permanent reference against which design decisions can be checked. The information recorded in Table A-2 serves as the basis for the design stage and for the more detailed design and maintenance decisions that are made at that stage.

Outdoor design temperatures 2.5% January 2.5% July degree days below 18°C	Seismic data Za Zv Zonal velocity ratio, v
Soil temperatures at various depths	Other vibration sources and loads
Indoor design conditions indoor temperature indoor humidity Air-borne contaminants	Wind design wind speed 1/10 hourly pressure 1/30 hourly pressure 1/100 hourly pressure
Precipitation 15 minute 1 day total annual driving rain index snow load (SS) snow load (SR)	Agents resulting from proposed uses (e.g., industrial processes, unusual occupancy loads) likely to affect durability
Ground conditions soil types at various depths depth to water table contaminants	Other relevant environmental agents and factors (e.g., pollutants, flooding, vibrations, mining subsidence)

Table 2: Structural and environmental loads recorded using CSA guide Table A-1

Design

Table A-3 "Comprehensive design life and maintenance decisions" in the Appendix of the CSA guide (see Table 3 of this paper) expands on Table A-2 and provides a structure for recording more detailed information on the materials, components, assemblies and systems selected or designed for the building.

		Building Design Service Life							
		Category		*long*		Period in Years		*60*	
		Building Component							
Building Element	**Materials or Type**	**Design Life**	**Failure Category**	**Maintenance, repair, replacement** Category	Type(s)	Freq'cy	Access	**Cost** Cap	Maint
2. Environmental Separation									
2.2 Int'r/Ext'r (Above Ground)									
2.2.5. Walls & Windows	*- glass curtain wall*	*60*							
windows	*sealed glazing units*	*25*	*costly*		*replace* *wash*	*25* *annual*	*swing stage*		
thermal insulation	*75 mm rigid glass fibre*	*60*		*none*					
A/VB system	*22 ga prefinish metal pan w/sealant and membrane*	*20*	*costly, interruption in use, risk of injury, danger to life*	*extensive*	*replace*	*20*	*swing stage*		
moisture protection - cladding	*6 mm tempered spandrel glass*	*40*		*extensive*	*inspect* *replace*	*10* *40*	*swing stage*		
- seals	*rubber sealant*	*20*	*costly*	*extensive*	*inspect* *replace*	*10* *20*	*swing stage*		
connectors anchorage	*s/s*	*60*	*costly, danger to life*	*extensive*	*inspect* *replace*	*10* *60*	*swing stage*		

Table 3: Excerpt of detailed record of design decisions to serve as basis for maintenance program (based on CSA guide Table A-3)

Note: The excerpt focuses on elements of the building envelope that might be found on a high-rise office building. Consequently, the means of access all indicate "swing stage". For low rise buildings, other building elements or minor repairs, access might be from the interior, or might be obtained from the exterior by scaffolding, bucket truck or ladder.

In the design stage, service life predictions are carried out for the building materials, components and assemblies. These are checked against the design service lives recorded in Table A-3. Where the predicted service life falls short of the design service life, the design must be adjusted or a decision must be made to accept a shorter service life.

To various degrees, the CSA, BSI and AIJ guides recognize that discussions on maintenance must begin at the earliest stages, since decisions on materials and design details will have significant implications for the type, frequency, complexity and cost of maintenance required to ensure the appropriate level of durability of materials and assemblies. Providing access to elements that require maintenance repair and replacement must be addressed.

Thus, information recorded in Table A-3 is critical, not only to the design process, but also to the development of the maintenance program. When complete, it provides a permanent record, for building owners and operators, of the information used to develop that program.

The focus in the CSA guide on structural and envelope elements allows for inclusion of specific recommendations related to detailing these elements for durability; for example, providing barriers and seals to resist infiltration and deposition of moisture or deleterious materials. Nine points are listed which address buildability/ease of construction.

The CSA and AIJ guides recognize that allowance should be made for alterations to the building to respond to functional obsolescence. As a service life rather than durability document, the AIJ guide goes further by stating that energy implications and social requirements should also be considered.

Tendering and contracting

For this stage, the CSA guide focuses on communication among the participants and confirmation of understanding of the component functions, materials and methods of construction, and performance assurance activities. This stage provides an opportunity either for the manufacturers and suppliers to confirm that the materials, components and installation methods specified will meet the performance requirements, or for the parties involved to revise the specifications.

Construction

The CSA guide focuses on assignment of tasks to the trades, and coordination and communication with the trades. Protection of building materials during construction is also highlighted. Additional information on specific QA and PA activities that should be carried out during this stage would be useful.

Handover

Though a critical stage with respect to QA and PA, handover is not addressed in the CSA guide. This omission is more a reflection of the resources available for development of the Guide than any conscious decision not to address the subject.

Operation and Maintenance

Only the CSA guide recognizes that the operating conditions of a building, which may for example result in pressurization or humidification, will have a significant impact on component and assembly durabilities, and that limits on indoor conditions specified at the design stage must be adhered to.

As indicated above, all of the guides recognize that discussions on maintenance must commence at the earliest stages in the building life cycle, since decisions on materials and design details will have a major effect on the type, frequency, complexity and cost of maintenance, repair and replacement.

The CSA guide discusses the preparation of a maintenance and inspection program, outlines information that should be compiled to support the program, and identifies the need to budget for implementation. Inspection is required to verify that maintenance has been carried out and to identify signs of deterioration.

The AIJ guide provides considerable detail on the development of maintenance plans including: the specification of the objectives of maintenance over the service life; maintenance works to respond to degradation; upgrading works to respond to obsolescence; the responsibilities of the various participants with respect to preparation of the maintenance plan and budget, information and document transfer, and training. Inspection as a distinct task within maintenance is not discussed.

Only the CSA guide addresses investigation, in which the agents and mechanisms responsible for deterioration are identified in order to develop appropriate repair or replacement strategies. Information is provided on the analysis and synthesis of evidence, methods of monitoring and testing, and issues to be considered in developing repair strategies.

Renovation

Of the three documents discussed, only the CSA guide addresses building renovation. The need to establish the existing building condition and potential changes in structural and environmental loads are discussed.

Implementation

Since it was published only in the fall of 1995, implementation of the CSA guide has been limited. Well before its release, however, the Guideline was used by PWGSC in the development of design and construction manuals on parking garages, wall systems and roof systems. References are appearing in other publications such as "Air Barrier Systems for Walls of Low-Rise Buildings" [5] published by the Canadian Construction Materials Centre (CCMC) at IRC.

The guide is being used by CCMC as a reference for establishing durability criteria and by building officials for guidance in defining design service life to help them determine the acceptability of building elements not described in the National Building Code (NBC) [6]. Because the guide is not enforceable, addressing as it does a process rather than a product, it is not referenceable in the requirements of the NBC. It is expected, however, that it will be referenced in the Appendix to this Code.

The CSA guide is being referenced by some building science consultants in building envelope assessment proposals and has been referenced in at least one building design tender document.

Because the CSA guide recommends compilation of a record of decisions related to service life, there is some level of resistance to adoption of the guide by designers and manufacturers, as such explicit specification of performance would increase their liability.

On the other hand, more forward-looking designers and building owners can be expected to recognize the advantages of designing, constructing, operating and maintaining buildings in such a manner as to improve durability.

Conclusions

As indicated in the Foreword to the CSA guide, "This guideline is a first attempt ...." As such it provides a base from which the industry can begin to build a consistent and comprehensive approach to addressing building durability. It fulfills its objective of providing information that is easily accessible to and usable by an industry that is not used to considering durability through the building life cycle.

While all involved in its development would agree that improvements could be made, the CSA guide compares favourably with other similar publications. As further indicated in the Foreword, "... users are encouraged and requested to submit any and all suggestions for improving and enhancing the information covered." It can only be hoped that the financial resources will be forthcoming to support further development.

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5. Air Barrier Systems for Walls of Low-Rise Buildings, National Research Council Canada, Ottawa, 1997.

6. National Building Code of Canada 1995, Canadian Commission on Building and Fire Codes, National Research Council Canada, Ottawa, 1995.

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The National Building Code: Durability Requirements and their Incorporation into an Objective-Based Structure

G. Adaire Chown and Igor Oleszkiewicz*

Abstract

The National Building Code of Canada (NBC) has for some time included a variety of durability-related requirements. This has been despite the fact that there has been considerable confusion as to how, and to what extent, the Code should address durability.

The paper suggests an approach to separating the concepts of durability and service life, and indicates the ease or difficulty with which these may be addressed in building codes.

This paper discusses conformance to, and enforcement of, durability-related requirements, and three technical issues that must be addressed in developing such requirements for codes: identifying the agents and mechanisms of deterioration to be resisted or accommodated, establishing appropriate degrees of durability, and establishing means for specifying those degrees of durability. In the context of these issues, the paper provides example requirements from the NBC, the US National Building Code published by Building Officials and Code Administrators International (BOCA), and the New Zealand Building Code.

Looking ahead to future developments, the paper introduces the concepts of objective-based codes and functional requirements, and explains how performance and prescriptive requirements can fit into the structure of an objective-based code. The paper identifies various means of incorporating durability-related requirements into an objective-based NBC and provides examples of the approach currently being investigated.

Keywords: acceptable solutions, building codes, building envelope, buildings, deemed-to-comply, design service life, deterioration, durability, failure, functional requirements, objective-based code, performance requirements, prescriptive requirements, service life, standards

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The National Building Code: Durability Requirements and their Incorporation into an Objective-Based Structure

G. Adaire Chown and Igor Oleszkiewicz

Introduction – the strategic plan for code development and implications for durability

To address the development of national model construction codes in Canada between 1995 and 2000, the Canadian Commission on Building and Fire Codes (CCBFC) published a strategic plan [1]. The plan identifies 6 goals and 23 consequential objectives, and proposes 58 possible strategies for working toward the goals and objectives.

Related to the overall goal of providing national model codes that meet the needs of all code users in Canada, there are two objectives that have direct implications for requirements pertaining to the durability of buildings, and the materials, components, assemblies and systems of which they are comprised:

- The first states that the scope of each code document is to be clearly defined in accordance with identified needs; this has implications with respect to whether durability is or is not addressed in the national model codes.
- The second states that all the model codes are to be current, understandable, justifiable, logical, flexible and coordinated. One strategy for achieving this objective is the development of an objective-based code structure.

This paper discusses the issues of addressing durability in the National Building Code of Canada (NBC) [2] and how durability-related provisions may be incorporated into an objective-based version of the NBC.

Durability and the scope of the National Building Code

The NBC has for some time included a variety of durability-related requirements. This has been despite the fact that there has been considerable confusion as to how, and to what extent, the Code should address durability. Discussions by the CCBFC have indicated some misunderstanding of durability and service life, and how these are and might be addressed in the Code. Although the preface of the 1990 NBC states that "... requirements for quality and durability that affect health and safety are appropriate" [3] questions have been raised, since publication of that document, as to whether durability should be explicitly recognized as being within the scope of the Code.

With the establishment in 1992 of a new Standing Committee responsible for Part 5 Environmental Separation, and that Committee's decision to address explicitly the issue of durability as it applies to materials, components and assemblies in environmental separators, the question of how to properly address durability in the Code was brought to the forefront. One consequence of the resultant discussions was agreement by the CCBFC that "durability is a factor appropriate for codes provided the concern is related to the objectives of the particular code and any requirements are clear, explicit and enforceable at the time of construction" [4].

Durability and service life

In the literature, there are numerous definitions for durability. Rather than attempt to provide the best definition, it is more important that the concept, and the difference between durability and service life, be understood.

For the purpose of this paper, durability of a material, component, assembly or system is related to its ability, at a specific point in time, to perform its required functions at or above a minimum level in its service environment and to continue to perform over a period of time. Durability depends on initial properties and rate of deterioration in a particular service environment; that is, on initial performance and the rate of deterioration of performance in the service environment. As durability reflects a snapshot in time, it can be considered independent of maintenance. Carrying out maintenance will alter the properties of the building element or its service environment; consequently, durability after maintenance will be different from that before maintenance. (See figure 1 and Example 1.)

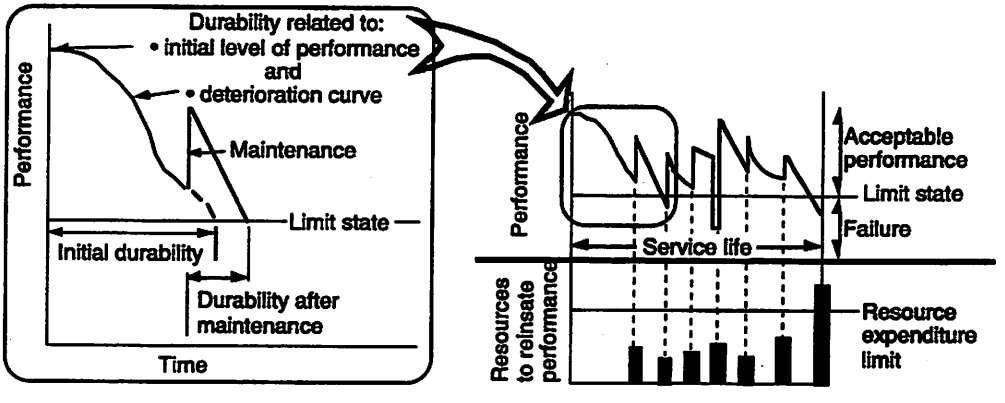

Figure 1: Durability, deterioration and service life

Durability and maintenance together determine service life. Service life is the period after installation during which an element performs its required functions at or above the minimum acceptable level without major costs or disruption for major maintenance or repair. When cost for maintenance or repair exceeds an acceptable level or when replacement is required, service life has ended. (See figure 1 and Example 1.)

Example 1: Service Life

NBC 5.6.1.1. Required Protection from Precipitation

The NBC requires, for buildings that do not fall within the scope of Part 9, that assemblies exposed to precipitation minimize ingress of precipitation into the assembly and prevent ingress into the building. Ingress is considered to be minimal where its occurrence is sufficiently rare, or accumulation sufficiently small, and drying sufficiently rapid to avoid material deterioration.

In a face-sealed cladding system, deterioration of sealant between cladding components will allow ingress of precipitation. Where ingress is such that deterioration commences, performance falls below the limit state and the cladding system, in effect, fails. Generally this means that the sealant has reached the end of its service life but the cladding system as a whole has not. If the sealant can be replaced for reasonable cost, the assembly will continue to function.

Obsolescence, or physical damage or deterioration of the cladding components themselves, may require, to re-establish performance, expenditure of resources that exceeds a certain limit. This limit may be based, for example, on life cycle costing. At this point, the end of service life has been reached. If the resources are expended to repair or replace the cladding components, the cladding system would acquire a new service life.

In the context of building regulations, it is important to differentiate between durability and service life. Durability may be addressed reasonably easily in a regulation, such as the NBC, that only comes into force up to and at the time of building hand-over. Having requirements refer to service life, as it depends on maintenance, is more problematic. These issues are addressed below under "Degree and specification of durability, and conformance and enforcement".

Specifying durability in building codes

When considering the inclusion of durability-related requirements in codes, issues that must be addressed include:

- identifying the agents and mechanisms of deterioration that must be resisted,
- determining acceptable minimum initial levels of durability,
- identifying means to specify the level of durability, and
- defining means to determine compliance and ensuring that the requirements can be enforced.

Mechanisms of deterioration

There are two possible approaches to identifying agents and mechanisms of deterioration that a code requirement is to address:

- attempt to identify all the potential mechanisms of deterioration that might be encountered in any situation, or
- refer to "expected" mechanisms of deterioration.

Identifying relevant mechanisms of deterioration

Where a code provision is concerned with a particular agent or mechanism of deterioration in a particular service environment, the first approach is simple. For example, to address HVAC equipment and the mechanism of freezing, a simple performance requirement may be sufficient.

NBC Part 6 Heating Ventilating and Air-Conditioning
6.2.1.9. Installation – General

1) Equipment forming part is a heating or air-conditioning system shall be protected from freezing if

a) it may be adversely affected by freezing temperatures and
b) it is located in an unheated area. [2]

If the code provision pertains to corrosion of brick ties installed in low-rise buildings, a simple prescriptive specification of weight of galvanizing serves the purpose.

NBC Part 9 Housing and Small Buildings
9.20.9.5. Ties for Masonry Veneer

1) Masonry veneer 75 mm or more in thickness and resting on a bearing support shall be tied to masonry back-up or to wood framing members with straps that are

a) corrosion-resistant,

.....

9.20.16.1. Corrosion Resistance of Connectors

1) Carbon steel connectors required to be corrosion resistant shall be galvanized to at least the minimum standards in Table 9.20.16.1.

Table 9.20.16.1. (excerpt)

Connector Material	ASTM Standard	Coating Class or Thickness
Sheet (less than 3.18 mm thick)	A 123	305 g/m² on material 0.76 mm thick

[2]

Where the provision addresses deterioration in a more general fashion, this approach becomes unwieldy. In these cases, it would be an onerous task to provide exhaustive lists of agents and mechanisms that affect specific building elements in particular service conditions.

Expected mechanisms of deterioration

The second approach has the advantage of addressing all the relevant agents and mechanisms but may raise questions as to what should be "expected". The answer will vary depending on materials selection, service environment, and what is considered "good practice" at any particular place and time. This approach recognizes that the designer ultimately bears responsibility for ensuring that the design is consistent with the current technical information and makes this assignment of responsibility more explicit.

Since 1970, Part 4 of the NBC has used this approach to ensure that all expected structural loads and effects of those loads are properly addressed in the design of the structural system.

NBC Part 4 Structural Design
4.1.1.3. Design Requirements

1) Buildings and their structural members including formwork and falsework shall be designed to have sufficient structural capacity and structural integrity to resist safely and effectively all loads and effects of loads and influences that may reasonably be expected, having regard to the expected service life of buildings, and shall in any case satisfy the requirements of this Section. [5]

In the 1995 NBC, this approach was adopted for a general deterioration resistance requirement.

NBC Part 5 Environmental Separation
5.1.4.2. Resistance to Deterioration

1) Except as provided in Sentence (2), materials that comprise building components and assemblies that separate dissimilar environments shall:

a) be compatible with adjoining materials, and
b) be resistant to any mechanisms of deterioration which would be reasonably expected given the nature, function and exposure of the materials. [2]

Degree and specification of durability, and conformance and enforcement

The terms compatibility and resistance to deterioration are qualitative and relative. It is quite clear where materials are completely incompatible or where no attention has been paid to resistance to deterioration. However, to develop requirements that will provide a reasonable degree of protection, the bases for selecting appropriate levels of compatibility and resistance, the means of specifying those levels, determination of conformance and ease of enforcement must be addressed.

Good practice

Many requirements related to durability are stated in such general terms that they essentially rely on good practice to achieve their intent. This is the case with the NBC Part 5 requirement presented above and with the example below:

NBC Part 9 Housing and Small Buildings
9.27.5.5. Fastener Materials

1) Nails or staples for the attachment of cladding and wood trim shall be corrosion-resistant and shall be compatible with the cladding material. [2]

Some requirements provide more guidance but still rely on the designer for a detailed specification of the materials and installation. The NBC provision for protection of steel lintels, for example, provides no indication of what quality of paint or method of application is required, or what other protection might be adequate.

NBC Part 9 Housing and Small Buildings
9.20.5.2. Lintels and Arches

4) Steel angle lintels supporting masonry shall be prime painted or otherwise protected from corrosion. [2]

Where the issue is simple and good practice well known, it may be easy to determine compliance and to enforce the requirement. Where the issue is more complicated, code officials must generally rely on professional accreditation to ensure compliance.

Specification of acceptable materials and components

Prescriptive specification of materials and components is the simplest approach to regulation. The description of the building element is clear and conformance is verifiable.

Such provisions, however, neither relate to, nor provide, any inherent basis from which to establish appropriate degrees of durability. As such, determining equivalence to such a requirement to determine acceptance of innovative products is problematic.

NBC Part 9 Housing and Small Buildings
9.27.3.1. Materials

1) Flashing shall consist of not less than
a) 1.73 mm thick sheet lead,
b) 0.33 mm thick galvanized steel,
c) 0.46 mm thick copper,
d) 0.46 mm thick zinc,
e) 0.48 mm thick aluminum, or
f) 1.02 mm thick vinyl. [2]

Where a number of materials are permitted by a prescriptive requirement, the requirement may in fact define a range of acceptable degrees of durability rather than a minimum. As no reference is made to the service environment, the requirement will inevitably specify a level of durability that is above minimum for less severe environments and may risk specifying a level below minimum for more severe environments. The quantity of information that would be needed to address all building materials in all assemblies in all service environments is enormous.

Specification of test criteria

Many code requirements refer to tests that a building element must pass in order to demonstrate acceptability. In the NBC, durability-related tests are generally called up through references to standards (see "Referencing material and component standards" below). In the US BOCA Code, references to these tests are more explicit.

> **BOCA Article 23 Roofs**
> **2304.3 Durability:** All roofs and roof coverings shall be of approved materials such that those properties which establish fire classification, wind resistance and weather protection shall be maintained in accordance with Sections 2304.3.1. and 2304.3.2. [6]

Sections 2304.3.1. and 2304.3.2. call up accelerated weathering and impact resistance tests. The correlation between these tests and durability in situ, however, are unknown. Such a requirement will inevitably specify a level of durability that is above minimum for less severe environments and may risk specifying a level below minimum for more severe environments. Determining conformance and enforcement of the requirement, however, is fairly straight-forward.

Specification of durability in terms of element design service life

Although no building element has an infinite service life, failure of an element generally presents a hazard to building users when the failure occurs sooner than expected, or when the expected time of failure is ignored. To avoid unexpected failure, codes can refer to the service life of the building element.

> **BOCA Article 21 Exterior Walls**
> **2101.2 Durability:** All exterior walls and components thereof shall be of approved materials which maintain the performance characteristics required herein for the duration of use. [6]

This type of requirement assigns to the designer the responsibility for establishing and documenting appropriate design service lives for the building elements based on some assumed level of maintenance. This approach presents two difficulties:

- The information required to establish reasonable design service lives for various building elements in various service environments depending on or independent of maintenance is generally unavailable.
- Because achievement of design service life may depend on maintenance, the actual occurrence of which is beyond the control of a building code and the designer, it cannot be assumed that the service life of a building element will in fact be achieved unless a particular maintenance program is carried out. If this is not understood, building owners, designers, manufacturers and constructors may bear a financial burden should litigation result from non-achievement of the design service life.

That is, unless the design service life is independent of maintenance or there is a widely accepted understanding of the maintenance required for the building element, and unless the service life is known for the service environment in question, conformance to and enforcement of requirements based on this approach are problematic. If it appears at all, this type of requirement is rare in the NBC.

Specification with respect to building design service life

The NBC Part 4 requirement discussed previously and the New Zealand Building Code specify building element durability with regard to building design service life.

New Zealand Building Code Clause B2 Durability
FUNCTIONAL REQUIREMENT
B2.2 *Building* materials, components and *construction* methods shall be sufficiently durable to ensure that the *building*, without reconstruction or major renovation, satisfies the other functional requirements of this code throughout the life of the *building*. [7]

This approach presents difficulties similar to those presented by requirements that specify durability in terms of building element service life. If the building element in question is essentially inaccessible so that its design service life is independent of maintenance, if its service life in the service environment is known, and if there is a general understanding of the appropriate design service life for the type of building at hand, this type of requirement may be workable. Otherwise, building owners and designers are required to assume liability for determining material and component service lives and documenting these and the building design service life. This type of requirement may be found in a very few instances in the NBC and its referenced documents.

Specification of service life recognizing implications of failure and cost of maintenance

New Zealand Building Code Clause B2 Durability
PERFORMANCE
B2.3 From the time a *code compliance certificate* is issued, *building elements* shall with only normal maintenance continue to satisfy the performances of this code for the lesser of; the *specified intended life* of the *building*, if any, or:

(a) For the structure, including *building elements* such as floors and walls which provide structural stability: the life of the *building* being not less than 50 years.

(b) For services to which access is difficult, and for hidden fixings of the external envelope and attached structures of a *building* : the life of the *building* being not less than 50 years.

(c) For other fixings of the *building* envelope and attached structures, the *building elements* having moderate ease of access but which are difficult to replace: 15 years.

(d) For linings, renewable protective coatings, fittings and other *building elements* to which there is ready access: 5 years. [7]

It is generally accepted that major structural components should last at least as long as the design service life of the building - the consequences of failure to resist structural loads being potentially very serious. Other elements may have service lives that are significantly shorter. Since health and safety hazards due to failure may arise where the expected failure is ignored, ease and cost for repair or replacement of these elements become health and safety issues.

Specifying durability in terms of the consequences of failure or costs of maintenance, repair or replacement is a refinement of the approach that simply refers to building design service life. As such, it bears all of the difficulties of previous approaches that depend on service life information.

In providing specific minimum service lives for particular types of building elements, the example requirement above from the New Zealand Building Code risks specifying degrees of durability beyond those actually needed. Designing the structure and building services for a 50 year service life would not be warranted for a building intended to have a 30 year service life. Though by far the minority, some buildings are intended to have very short lives. In these cases, a building element service life of 15 years, and possibly even 5 years, may be unreasonable.

This type of requirement does not appear in the NBC.

Referencing material and component standards

Referencing standards transfers the difficulties identified above from the code writers to the standards writers. The approach requires that conscientious code writers be aware of the means used by the standards writers to specify levels of compatibility and resistance, and of the levels that those writers have deemed to be appropriate.

As many standards from many organizations are referenced in codes, it is difficult to achieve a coordinated and consistent approach to durability. A review of standards from a single standards development organization reveals a range of approaches.

NBC Part 5 Environmental Separation

5.6.1.2. Protective Materials and Component Properties

3) Where materials or components applied to vertical assemblies are installed to provide required protection from precipitation and are covered in the scope of the standards listed below, the materials or components shall conform to the requirements of the respective standards:

... q) CSA A371, "Masonry Construction for Buildings", Section 4, ... [2]

CSA A371 Masonry Construction for Buildings, Section 4

4.1.2 Clay or Shale Masonry Units

Clay or shale masonry units shall conform to one or more of the following Standards:

...

A82.1-M, Burned Clay Brick;

....

4.3.2 Connectors (Anchors, Fasteners, Ties, and Joint Reinforcement

Connectors for masonry construction shall conform to CSA Standard CAN3-A370. [8]

CSA A82.1-M, Burned Clay Brick

5.1 Durability

5.1.1

The brick shall conform to the physical requirements for the grade specified as prescribed in Table 2. .... [9]

CSA Standard CAN3-A370-M, Connectors for Masonry

4. Corrosion Protection

4.1 Effective Life

Masonry connectors, shelf angles, and secondary support framing for masonry shall have sufficient protection against corrosion to enable them to maintain their strength, stiffness, and anchorage and to function effectively for the intended service life of the building. [10]

Table 2 of CSA A82.1-M provides criteria for compressive strength, water absorption and saturation coefficient for brick. Test methods are provided in CAN3-A82.2M, "Methods of Sampling and Testing Brick" [11]. This type of requirement, to which compliance is relatively easy to determine, is in stark contrast to that in CAN3-A370-M which refers to building service life.

The optimum approach

Depending on one's point of view, each approach discussed above has its advantages and disadvantages. Some provide more flexibility for designers; some impose greater liability. For some, compliance is easy to determine; for some it is very difficult if not impossible. The current mix found in the NBC can be expected to continue, with some effort directed toward determining the level of durability provided by prescriptive requirements and toward providing means to determine compliance or identifying deemed-to-comply solutions where ascertaining compliance is difficult. These developments will be supported by the transition to objective-based codes.

Objective-based codes

What is an objective based code?

For any regulation, there are objectives that it is seeking to achieve. In the case of the NBC, the two most widely recognized and accepted objectives relate to the provision of healthy and safe conditions for building users. To address these objectives, one may identify a number of consequential objectives.

For example, to minimize the risk of unsafe conditions, one must protect users from fire and structural failure. To minimize the likelihood of structural failure, providing strength and resisting deterioration are consequential objectives. To reduce the likelihood of premature deterioration due to corrosion, biological factors or freeze-thaw cycling, consequential objectives may relate to material properties or the moisture content in building assemblies. The control of moisture in an assembly depends on the moisture sources and transfer mechanisms. To control moisture transfer, one would expect to find objectives related to air leakage, vapour diffusion and the forces that can drive rain water into an assembly. In this manner, a hierarchy of objectives can be developed.

At the bottom of the hierarchy, the objectives become sufficiently specific that they address particular building elements and provide criteria. These objectives are referred to as functional requirements. These may be qualitative or quantitative. For example, to control moisture transfer by air leakage, a qualitative functional requirement might state:

> Transfer of indoor air into environmental separators, where moisture in the air may condense in the separator, shall not exceed a rate at which deposition and accumulation will result in premature deterioration.

In quantitative terms, the same functional requirement might state:

> Transfer of indoor air into environmental separators, where moisture in the air may condense in the separator, shall not exceed 0.5 $L/(s \cdot m^2)$ measured at an air pressure difference of 75 Pa.

To comply with a functional requirement, a variety of solutions may be developed. These are referred to as acceptable solutions. Construction that satisfies the requirements provided in the current NBC represent one set of acceptable solutions. The air barrier system requirements in NBC Part 5 Environmental Separation and Section 9.25 Heat Transfer, Air Leakage and Condensation Control might constitute solutions that would be acceptable for fulfilling the functional requirements provided above. An alternative solution, that might be appropriate in some circumstances, may involve depressurization of the building.

Thus, objective-based codes are simply codes whose provisions are related to a hierarchical structure of objectives. The structure consists of three types of elements: objectives, functional requirements and acceptable solutions. Provisions that describe acceptable solutions may be stated in either performance or prescriptive terms. As such, an objective-based code is not solely a performance code or a prescriptive code but allows for the development of numerous solutions, described in performance or prescriptive terms, to achieve the stated objectives.

Steps toward development of an objective-based code

Two activities are being carried out in the first stage of the transition to an objective-based NBC. One is a top-down development of the objective hierarchy. The other is a bottom-up analysis in which intent statements for each and every requirement in the Code are being developed. Stating the intent of the requirements will not only provide immediately a large volume of useful information to code users, but will also indicate the relationship between the requirements and the hierarchy of objectives.

Because the Code has developed over decades with numerous committees addressing issues on a piecemeal basis, this exercise is truly one of discovery. Intents of requirements are being found to relate to objectives that were previously not thought to be addressed by the Code. Consequential objectives are being identified for which no code requirements exist. The process is revealing the true scope of the current Code and identifying areas where rationalization is needed.

Fitting durability into the objective structure

Because the development of the objective hierarchy for the NBC is in progress, it is not possible to describe how any one requirement or a set of requirements will be addressed in the final objective-based Code. The question of fitting durability-related objectives and provisions into the structure has been a matter of considerable discussion.

At various times, durability has been assigned specific positions within the objective tree and has also been relegated to a third dimension, parallel to the tree, such that durability-related objectives and provisions can be related to any number of objectives and provisions in the basic structure.

Figure 2 illustrates an approach that is currently being considered for relating existing durability-related NBC requirements to the objective structure. This approach identifies and addresses durability where it naturally appears in the objective hierarchy. The example relates three existing requirements to the root objective of providing safe conditions for building users. Many other requirements in the Code also respond to this root objective and its consequential objectives, and similar examples could be related to other root objectives.

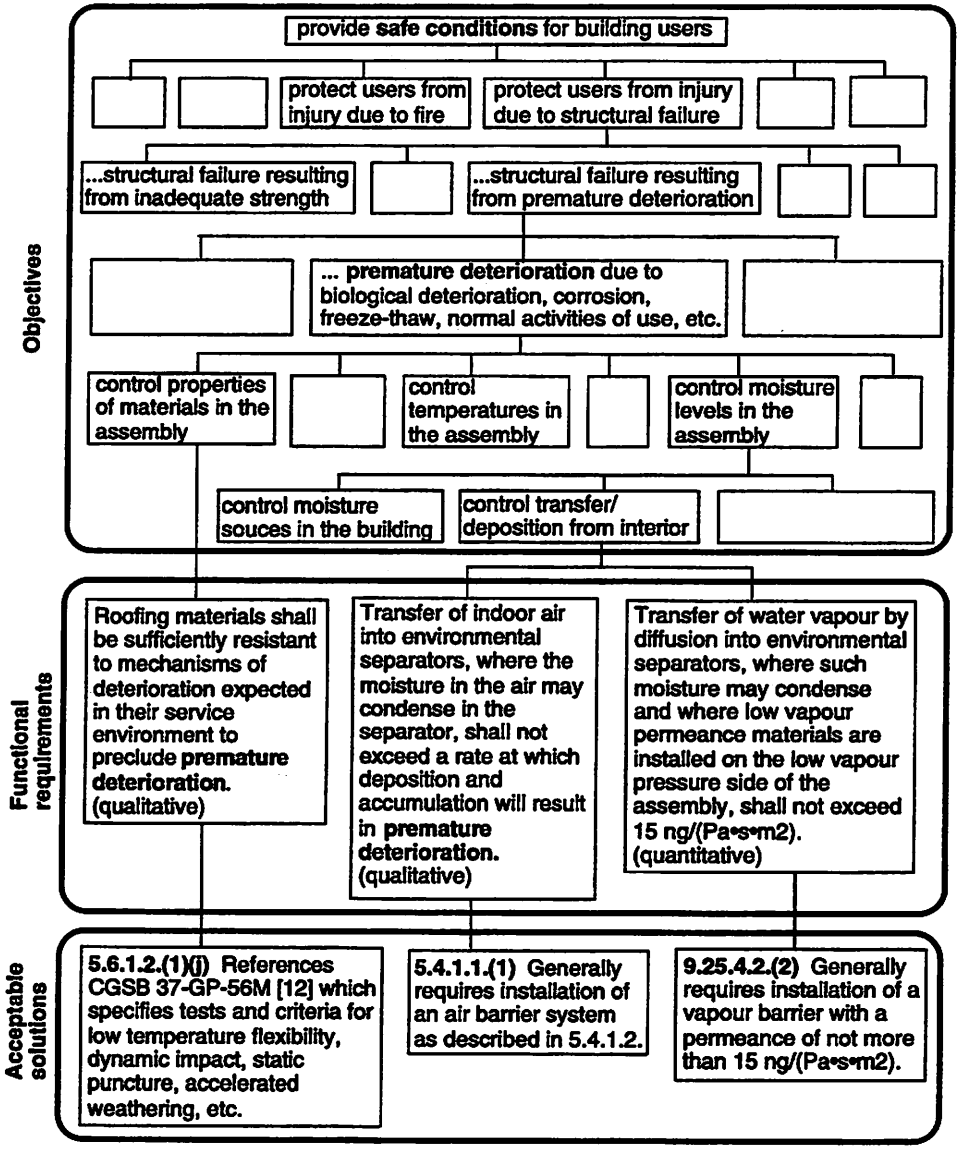

Figure 2: Example of objective progression with related functional requirements and acceptable solutions

Opportunities and challenges

Because an objective-based code permits a large number of acceptable solutions to meet its objectives, there are numerous means of providing for durability that are not currently specified in the Code. The development of the objective-based NBC opens the doors to the development of these alternative solutions.

Although the levels of durability provided by prescriptive Code requirements are largely unknown, the current requirements reflect acceptable solutions. The first challenge is to determine what are the currently acceptable levels of durability. Once these are defined, there is a basis for determining whether proposed solutions meet the related durability objective.

Where current requirements are stated in terms of service life, means must be developed to determine compliance. Development of intent statements for the Code provisions should help to identify instances where requirements related to service life are provided in the referenced standards.

Summary

Any mention of addressing durability in building codes can raise a storm of questions and concerns. For a building code to serve a useful purpose, however, it must ensure an acceptable level of performance of the building and its elements for some reasonable period after hand-over.

This paper has described the approaches used in the current NBC to address the issue, identified approaches used in other codes and discussed the advantages and disadvantages. The transition to an objective-based NBC provides an opportunity to review the durability-related requirements currently provided in the Code and to identify areas where rationalization and further information are needed to assist in determining compliance.

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LIMIT STATES DESIGN FOR DURABILITY

by D. E. Allen[1] and M. T. Bomberg[2]

Abstract

The method limits states was originally developed for the design of structures to satisfy performance requirements for safety and serviceability. This paper extends its application to include durability. For this purpose, one must first select a required period of service (design life) for the component of the building envelope and then apply the limits states method as presented in this paper.

Key words: building envelope design, limits states method, long-term performance, durability, service life, damage functions, deterioration mechanisms.

INTRODUCTION

The new CSA guideline on durability in buildings (CSA S478-95) contains the basic durability requirement that the building and its components be designed, built, operated, maintained and repaired in such a way that the required performance is maintained during its design (service) life for typical, foreseeable environmental conditions. The design life of any building component can be specified (in categories ranging from 5 to 100 years) depending on a number of factors. The selection of the design life also depends on the accessibility and the ease with which the building component can be repaired or replaced.

The next step is more difficult. One must predict what the service life (time to failure) of any component will be. CSA S478 lists three methods to predict service life - experience (demonstrated effectiveness), modeling and testing. Experience is applicable to systems/ materials that have stood the test of time under specific environmental conditions. Modeling and testing are required for innovative materials and systems as well as for traditional materials or systems that are to be exposed to different environmental conditions. Although much modeling and testing is currently available, the validity range of these tests or models is often questioned. To assist building professionals in the design process one should integrate these models and test information into one practical tool.

There is one such practical tool, the limit states design (formerly allowable stress design) though this tool is used for the evaluation of structural performance of any system that does not deteriorate. This paper redefines limit states design , which currently is strictly mechanical, to include deterioration, thus involving a much broader range of natural phenomena. Based on this redefinition, the process to which the limit states is applied is given in Figure 1.

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Figure 1: The process evaluated by the limit states method

Loads and stresses in Figure 1, reflect chemical and biological agents of deterioration as well as mechanical forces and movements. Examples of stresses include time-of-wetness (appropriately defined) and mechanical stresses such as force acting on a given area. Failure is defined when a stress exceeds a limiting value corresponding to the onset of failure, i.e. a limit state, when a component ceases to perform its function. An appropriate safety factor, that depends on the consequences of failure, may be included in the definition of failure. For cumulative processes such as fatigue or corrosion, the predicted service life may be defined as the period of time needed to reach the limiting stress. For non-cumulative processes such as fracture under mechanical stress, the probability of failure during the design life is controlled by comparing the maximum probable stress with a limiting value.

The key to durability design is either to prevent or to delay failure by exerting control in one or more of the steps in the process depicted in Figure 1. This process will be defined in more detail as it relates to building envelopes. It is common practice for the designer, during the initial design of a building envelope, to specify a system of components, each used for a specific function (e.g., insulation, air barrier, rain screen, structure), and then to evaluate the proposed envelope for all of its functional requirements, including the durability of its components. The process defined in Figure 1 is therefore used to evaluate a proposed design or to investigate an existing building envelope.

LOADS

Structural loads acting on building envelopes include forces due to snow, wind, earthquake, component weights, and air pressure differentials across the component. Other factors, e.g., loads causing abrasion such as wind-driven sand on the surface of the envelope may need to be also considered. Later in the limit states design process, we will also consider differential movement of the envelope as a "stress".

Environmental loads acting on building envelopes include agents which may cause deterioration, such as moisture in its various phases, air and soil (ground) constituents, as well as various contaminants in moisture, air and soil. Furthermore, biological agents and solar radiation are also environmental loads. Temperature is another environmental load which results in both structural effects, such as differential movement, as well as environmental effects such as condensation and frost action.

Table 1 provides a list of loads acting on building envelopes. When thinking of environmental loads on buildings, one should think of the origin of the load (indoor or outdoor environment) and where these loads are applied to the building.

Category	Agent	Type
Structural	gravity	snow, dead load
	lateral	wind, air, earthquake
Environmental	constituents	solid phase (ice, snow)
Moisture		liquid (rain, condensation)
		gas (water vapour)
	contaminants	chlorides, acids
Air	constituents	oxygen, carbon dioxide
	contaminants	oxides, particulate, sea spray
Soil (ground)	constituents	sulfates, chlorides, acids
	contaminants	chemical spills, road salts
Biological agents		microorganisms, insects, birds
Solar radiation		ultraviolet radiation
Temperature		thermal stress

Table 1: Loads acting on building envelopes

TRANSFER MECHANISMS

Load transfer mechanisms are basic to engineering practice. A simple analysis of load transfer is one of the most useful tools when checking the design, not only for the structural system as a whole, but for connection details which are usually the Achilles heel of collapses that occur in practice. The free-body force diagram provides one such a tool for assessment or calculation. Structural loads on building envelopes have to be transmitted through the envelope into the structure, and through the structure into the foundation.

While there are many kinds of mechanisms for transferring environmental loads, two features of the transfer mechanisms that are important for practice, namely, driving forces and control measures. For instances, driving forces for transferring water through building envelope materials and systems include:

- gravity (force)
- momentum (kinetic energy)
- air pressure (convection or force)
- capillarity (surface tension)

These driving forces are illustrated in Figure 2 for rain penetration of the building envelope. Driving forces for transferring indoor air and water vapour through the envelope, where water vapour can condense inside materials include temperature gradients, air pressure differences, and vapor pressure differences.

The envelope is a system that must resist these driving forces. Although transfer mechanisms for environmental loads may be more complex than those for structural loads, they can be more effective as measures to divert environmental loads from becoming environmental stresses within the building envelope. Structural loads cannot be diverted in this way. The basic control measures are:

- Barriers
- Drainage
- Ventilation and drying

Environmental barriers include air, rain barrier and vapour retarders (barriers). They are simple and effective, although their -impermeability- is difficult to ensure during the design life. Drainage includes shedding of rain water from roofs, drainage collection systems, and appropriate detailing of surfaces exposed to environmental stresses. Examples of drainage measures, including the drip model, are illustrated in Figure 3. Ventilation and drying include provision of paths through the wall or roof space, with appropriate openings for air circulation due to air pressure differences. The rain screen model (Figure 4) is a very useful control measure which combines shedding, drainage and ventilation.

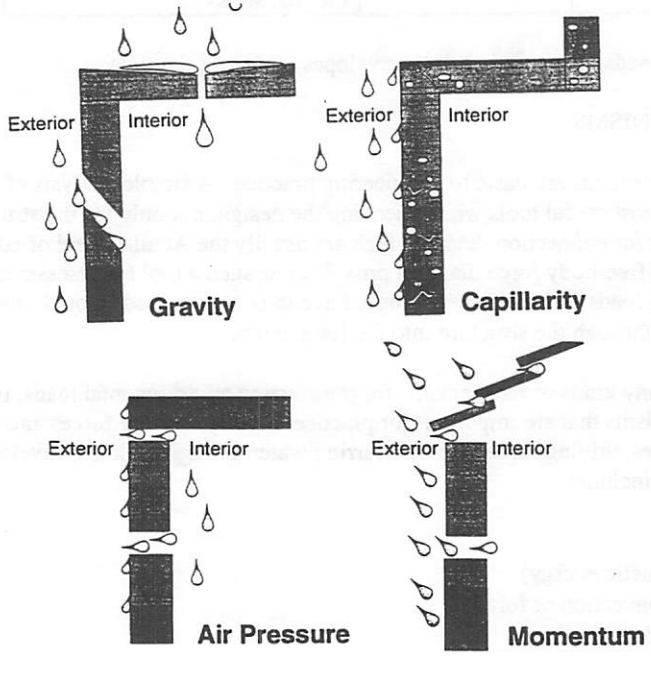

Figure 2. Driving forces for rain penetration (from NBCC, 1994)

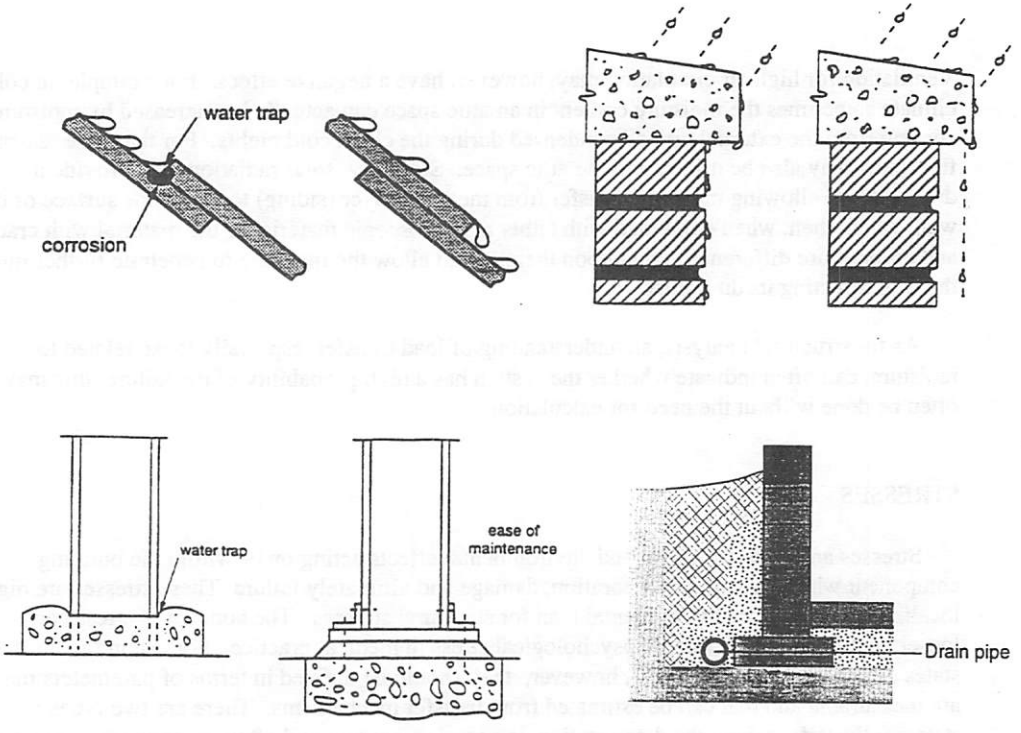

Figure 3. Drainage control measures (from CSA S478-95 and NBCC, 1994)

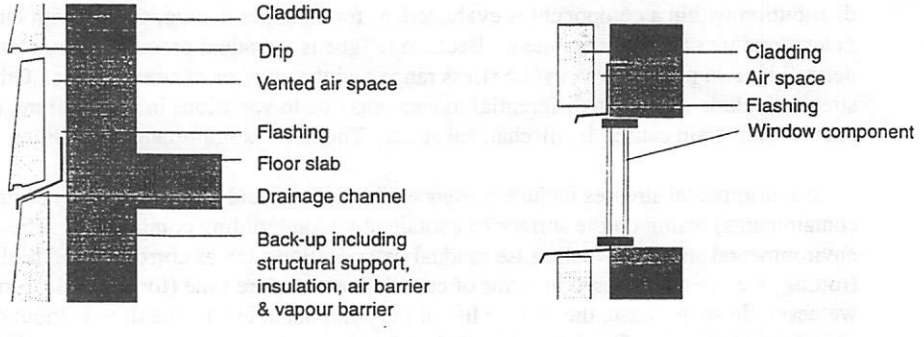

Figure 4 The rain screen (from NBCC, 1994)

Ventilation for high air circulation may, however, have a negative effecs. For example, in cold climate sometimes the moisture content in an attic space can actually be increased by moisture coming from the external air and condensed during the clear, cold nights. For the same reason, fine snow may also be driven into the attic space. Similarly, solar radiation may provide a driving force allowing moisture transfer from the outer layer (siding) to the inside surface of the wall, which then, when combined with either a hygroscopic material or the material with crack and air pressure difference acting upon them, could allow the moisture to penetrate further into the wall affecting its durability

As for structural analysis, an understanding of load transfer, especially those related to moisture, can often indicate whether the system has a high probability of the failure; this may often be done without the need for calculation.

STRESSES

Stresses are those structural and environmental effects acting on or within the building component which promote deterioration, damage and ultimately failure. These stresses are highly localized, more so for environmental than for structural stresses. The concept of stress can be loosely defined, as for example psychological stress in medical practice. For use in the limit states design process in Figure 1, however, they should be defined in terms of parameters that are measurable and that can be estimated from transfer mechanisms. There are two types of stresses: those for which the deterioration/damage is a gradual and often compounded process (e.g. corrosion, fatigue), and those for which the damage is sudden and unaffected by previous stress history. The former is identified as cumulative stress, the latter as reactive stress.

In structural practice, average stresses are defined as force acting for given cross-sectional area (in tension, compression or shear) or moments (in bending or torsion). Sometimes the stress distribution within a component is evaluated, as for example in components with large gradients in temperature or moisture content. Because fatigue is a gradual process, cumulative stress is defined by two parameters - cyclic stress range and the number of stress cycles. Other structural stresses include strain and differential movements due to variations in temperature, moisture content and strain caused by mechanical stress. The latter is important for building envelopes.

Environmental stresses include presence of water, air, and soil constituents (with or without contaminants) acting on the surface or contained within building components. The environmental stresses which cause gradual deterioration such as corrosion and biological decay (rotting) are often expressed in terms of cumulative exposure time (for example, time-of-wetness). In such a case, the service life of the component equals the time without deterioration plus the cumulative (often intermittent) time for the process to continue until resulting in failure. Sometimes, a gradual environmental stress may be approximated by a reactive stress. For instance, freeze-thaw cycles resulting in frost damage, can be estimated from a -worst case-scenario based on the simultaneous occurrence of a decrease in temperature below freezing and material saturation coefficient above a limit (Bomberg and Allen, 1996).

Spatial variation of temperature, or temperature variation over time is not really a stress, but it is an important parameter of the environment stress because such variations result in thermal stresses, hygric and thermal movements (often differential), condensation, moisture transfer which for many porous materials may affect the probability of surface spalling under action of salts or freezing temperatures.

Category	Type/Agents	Parameters
Structural:	force	force, stress, stress cycles
	expansion/contraction	strain, differential movement
Environmental:	moisture plus contaminants	cumulative exposure time
		saturation, time-of-wetness
	air constituents / contaminants	cumulative exposure time
	biological agents	cumulative exposure time
	ground constituents / contam.	cumulative exposure time
	solar radiation	intensity UV ray exposure
	temperature	extreme temp. gradients
		freezing temperatures
		freeze-thaw cycles

Table 2: Stresses on or in building envelope components

DETERIORATION/DAMAGE MECHANISMS

Damage mechanisms caused by mechanical stress such as fracture, yielding or buckling of structural components are relatively simple. Deterioration processes leading to damage or disfigurement of components are more complex because often more than one process is involved. For example, corrosion of reinforcement is followed by delamination of concrete cover in some cases, fracture of prestressing wires in other cases, and discoloration of visible surfaces by corrosion product stains in still other cases. The driving mechanism in this process is corrosion and the failure manifestations are concrete delamination, fracture of prestressing and discoloration.

The driving forces (term driving mechanisms is used in CSA S478) of deterioration/damage are the most important for practical consideration. The first and the most important step is to be aware of and to understand where deterioration mechanisms can occur and what environmental stress agents are accelerating the damage process. A checklist of driving mechanisms of deterioration/damage is contained in Appendix D of CSA 478. Different materials are listed along with the environmental stress agents under which damage may occur and with control measures to avoid failures. As an example, Table 3 contains the checklist for stone.

The most costly, often unforeseen, and perhaps the least addressed by building codes, durability risk is corrosion. Appendix E of CSA S478 is therefore devoted to providing a better understanding on where and under what environmental conditions corrosion will occur.

Material	Mechanism	Failures	Conditions for Process	Avoidance	References
Stone	Acid attack	Disintegration	Carbonates in stone	Choice of stone	ASTM C97
porous to	(leaching)	disfigurement	(e.g. limestone or	mortar pointing	Amoroso &
varying			sandstone, acid rain,	protective	Fassina (1983)
degrees			drainage, orientation	coating	BS 7543
crack sus-	salt crysta -	Spalling,	Salts in mortar or	Draining details	Kulak & Smith
ceptible at	llization	occasionally	adjacent materials	dampproof	(1993)
planes of		efflorescence	(e.g., ground)	course	ISO 6241
weakness	Freeze/thaw	Spalling	Water in pockets	Drainage details	
inorganic			freeze/thaw cycles		
	Movements	Bowing of	Type of stone	Use thicker	ASTM C97
	due to	panels	(marble), thickness	section or stiff	
	moisture			backing	

Table 3: Deterioration mechanisms for stone (from CSA S478)

FAILURE

Deterioration and even the local damage does not necessarily mean functional failure of the components or system. The damage must result in functional failure of components as defined in CSA S478 in terms of the following limit states:

- Collapse, as related to human safety or to loss of function of the building
- Local damage, as related to loss of function of the building component or to appearance
- Displacement, as related to loss of function of the building component or to appearance
- Discoloration, as related to appearance of components having an aesthetic function

To this list can be added unacceptable loss of performance (loss of function) if a property requirement was explicitly defined as a limit state criterion. Typically properties such as thermal, fire or noise resistance are used. Failures associated with deterioration mechanisms for building materials are listed in Appendix D of CSA S478 (see Table 3).

Much can be done to approximate the component service life based on a conceptual understanding of the primary mechanisms of load transfer and deterioration/damage that can occur. More specifically, one follows the limit states design process starting from the loads that are applied, the transfer mechanisms that drive or control the transmission of these loads, the resulting stresses and the deterioration/damage mechanisms which can occur under these stresses, and finally functional failure as described by the limit states. These qualitative judgments do not require any calculations or testing.

More accurate predictions require testing and mathematical modeling, much of which is available for specific systems and environmental loads. This predictive process can, however, be simplified into practical calculations based on the concept of stress limits.

STRESS LIMITS

Failure occurs when the damage becomes sufficient to initiate loss of function of the component.

For reactive damage processes, such as damage due to excessive force, the maximum stress during the design life must not exceed the stress corresponding to the onset of functional failure of the component, as defined by a limit state, with an appropriate safety factor (or probability of failure). Most of these stress limits are already incorporated in structural practice, either in terms of component resistance to forces, or in terms of deflection or vibration limits.

For gradual deterioration / damage processes, the cumulative stress at the end of the design life should not exceed the stress corresponding to the onset of functional failure of the component, including an appropriate safety factor depending on the consequences of failure. If cumulative exposure time is the stress parameter, the stress limit will depend on the stress agents as well as the presence of moisture. In CSA S478, this performance requirement is stated as follows: the predicted service life, which occurs when the cumulative stress reaches its limit, must exceed the design life of the component. With fatigue being an exception, there not many clearly defined limits for cumulative stress which could be used in the durability design.

EXAMPLE OF SERVICE LIFE PREDICTION

As an example of service life prediction, consider metal roofing subjected in time to fluctuating wind suctions, where failure typically occurs in the thin sheet metal surrounding the connectors to the roof structure. Figure 6 shows an S - N curve for a typical connection detail, where S is the stress range (in this case expressed as a percentage of the static pull-out resistance) and N is the number of cycles to failure due to tearing of the sheet metal. Figure 6 shows, for example, that the limit for 1000 cycles stress range is approximately 20 percent of the static pull-out resistance, thus indicating a considerable likelihood of failure due to low-cycle fatigue.

If there was only one stress range, Figure 6 could be used for predicting service life in years by dividing the number of cycles to failure, N, by the number of cycles per year, n. In general, however, there are more than one stress range, in which case the predicted service life, SL, is obtained from Miner's combination rule [XX] as follows:

$$SL = 1/_{\Delta} (ni/Ni) \qquad (1)$$

where, for each stress range Si, ni is the number of cycles per year and Ni is the number of cycles to failure.

For example, if there are, on average, 2, 10 and 40 cycles per year at wind stress ranges of 40%, 25% and 15% of the static pull-out resistance then, from Figure 6, the cycles to failure are 100, 700 and
2000 cycles respectively. Application of Equation (1) results in a predicted service life of

$$SL = 1/(2/100 + 10/700 + 40/2000) = 18 \text{ years}$$

which is rather low given that there is no safety factor. If the spacing between connectors is decreased so that the wind stress ranges are reduced to 30%, 19% and 11% of the static pull-out resistance respectively, then from Figure 6 the cycles to failure for these stress ranges are 300, 2000 and 5000 respectively, and the resulting service life from Equation (1) is 51 years.

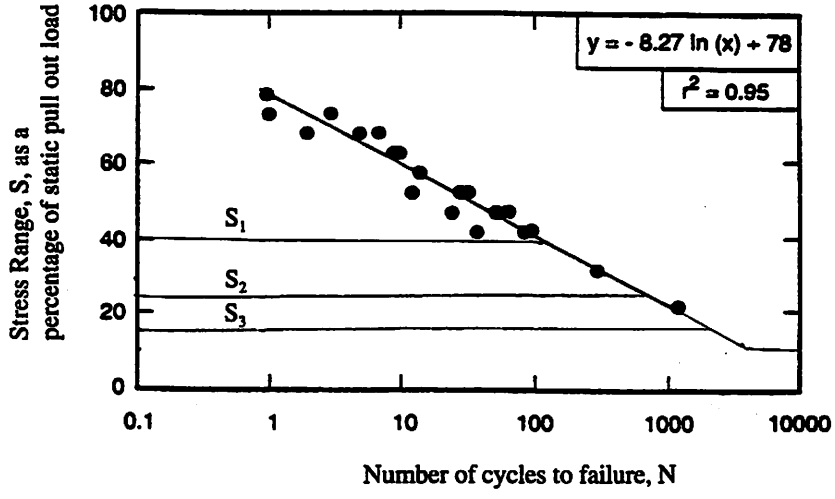

Figure 6. Fastener pullout failure of sheet metal roofing under cyclic loading (from Baskaran and Dutt, 1995)

It may be possible to arrive at a simpler design criterion for a standard design life, for example 25 years, based on the NBC design wind pressure for cladding and a resistance factor, f , applied to the static pull-out resistance. Such a simplification requires research to determine scope of application. Alternatively, a test standard can be prescribed for low-cycle fatigue resistance of metal roofing connection details, which incorporates a cyclic loading function appropriate for the wind regime. Such a test standard has been implemented for cyclone areas in Australia (Mahendron, 1995).

CONCLUDING REMARKS

This and a companion paper (Bomberg and Allen, 1996) generalized the limit states method for evaluating durability and long-term performance of building envelopes. The previous paper used more complex language, and defined such terms as:

Limit state criterion: $S_i < R_i$. This criterion implies, that for a particular performance aspect, one checks if the performance indicator is does not exceed the performance limit during the design life. The prediction of service life is associated with variability in phenomena (including environments and material properties), and uncertainties associated with testing and modeling. Safety factors are therefore introduced, the safety factors must be established based on the consequences of failure.

Performance aspect. This term is used to describe the primary process of the total deterioration / damage mechanism leading to functional failure. Performance aspects include corrosion, decay, fatigue, force (stress), movement and instability.

Performance indicator is a parameter, S_i, used in the damage function for each performance aspect, which provides a measure of performance (or, conversely, damage) at the end of the design life. The performance indicator may vary over the design life in which case the extreme value is used. The performance indicators include either physical characteristics, such as stress, strain, deflection, differential movement, loss of mass or area, thermal or noise resistance or a generalized performance indicator called the cumulative exposure time.

Performance limit, R_i is the value of the performance indicator, denoting onset of failure. Normally it is based on testing under appropriate failure conditions. This is either a traditional limit states criterion (e.g. limit on force, stress, strain and deflection or number of stress cycles) or the limit of the cumulative exposure time (LCET) i.e., the limit of the exposure period ascribed to a specified type of failure.

The concepts used in the proposed evaluation method are summarized in Table 4. If deterioration is cumulative, the initial performance indicator equals zero. With time, and in accordance with the damage function, the performance indicator gradually increases until it reaches the performance limit. The limit state for the analyzed performance aspect has been reached and the service life ended. The question is whether this happens before or after the design life of the component.

The GLS evaluation method allows two ways of dealing with a safety factor:

- either the performance limit or the loads may include the safety factor (explicitly or implicitly) as in allowable stress design
- a small probability of occurrence of one or more modeling parameters may be specified in lieu of a safety factor

If the limit state criterion is not satisfied (service life was shorter than the design life) , one can alter either the design or modify the design life of the component. Otherwise, one continues to examine other performance aspects for the same design or returns to a general evaluation.

While the previous paper presented the concept of the Generalized Limit States (GLS) method and underlined the need for quantifying models of the damage process (damage functions), the response to the paper indicated to the authors that the concept appeared to be intellectually interesting but with little or no significance for the designer / engineer. That is not what we believe. Therefore, in this paper the authors stressed the importance of the simple, practical and proven means (models). Both these papers aim rather at introducing a different way of thinking, than a specific technical information. The design based on limit states approach can be used with different models, either simple, as presented in this paper, or complex and based on computerized description of the damage function and the environmental loads. Whichever models are used the process described in Table 4 is fully applicable.

STEP	GLS METHOD
1	**select loads applied** to the envelope
2	**establish loads acting** on and within the envelope components
3	**select performance aspect and performance indicator** that relates deterioration / damage process to service time
4	**establish the maximum value of the performance indicator**, S_i, during the design life by application of the damage function
5	**establish the performance limit**, R_i, denoting onset of failure, (based on testing or economic judgment).
6	**check the limit state criterion**, $S_i < R_i$. If the predicted performance indicator is lower than the performance limit, changes must be made.

Table 4. Generalized Limits State evaluation of building envelope for durability as defined by Bomberg and Allen (1996).

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DURABILITY STANDARDS APPLIED TO A CORRECTIONAL FACILITY AT NORTHERN ONTARIO

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Abstract

This paper deals with several issues involving various components of the building as they relate to CSA Standard S478-95 "Guideline on Durability in Buildings".

This four-year-old "Design-Build" correctional facility exhibited premature performance problems arising from inadequate quality control during construction. Durability problems which were evidenced during the first few years of service resulted from moisture infiltration through the exterior walls and cracking of the brick veneer at several locations. Severe bulging of the brick veneer eventually required the closing of one area of the building. Additional deficiencies in the original construction related to the site grading, escape barriers, lateral stability of masonry walls and mechanical ventilation system also compromised the service life and durability of the facility. Various solutions were devised and evaluated to address these problems. Reconstruction work was undertaken with special attention to construction procedures and scheduling so as to minimize disturbances to the operation of the correctional facility and to maintain security. These special construction conditions resulted in higher than normal costs for re-construction.

KEY WORDS: Building envelope; Durability; Escape barriers; Service life; Quality Assurance.

Introduction

The correctional facility is used for the treatment of up to 100 inmates who are nearing the end of their sentences. Original design and construction was implemented using the "Design-Build"

approach and was completed and occupied in 1990.

The building is a single-storey structure with a plan area of over 7,000 square metres with exterior concrete block and brick cavity walls throughout. The roof structure is a hollow core prestressed concrete slab system. The layout of the building is shown on Figure 1.

Since construction was completed in 1990, the correctional facility has experienced a number of ongoing problems which include the following: rainwater penetration through the exterior masonry walls, accumulation of moisture and consequent frost problems in the exterior cavity walls, deterioration of exterior brick veneer, excessive heat loss, deterioration of paved areas, deterioration and failure of fibreglass escape barriers, operational problems with the exercise yard sliding security gate and mechanical ventilation system problems.

Problem

During the building's original one-year warranty, and continuing until 1995, cracking and deterioration of the existing brick masonry occurred, resulting in extensive leaks through the exterior masonry walls. Localized repairs were carried out where deterioration and cracking became severe. The poor performance of the building envelope seriously compromised the operational viability of the facility. Furthermore, improper drainage of the site resulted in heaving of paved areas and localized water ponding adjacent to the building.

In early 1994 two major concerns were identified with respect to the brick masonry. The first was an area of significant bulging of brick at the exterior wall at the exercise yard. The area adjacent to the bulging was closed because of possible collapse of the brick masonry. The second concern was noted during remedial work carried out to repair leaks. When the cap flashings were removed to facilitate repairs, it was discovered that masonry ties were missing or improperly installed at many locations.

A detailed investigation of the entire complex was carried out to identify all of the components which affected durability. The investigation included the following: test openings in the cavity walls at various locations to inspect the quality of the wall construction, inspection of the roofing

system, thermographic scan of the building to identify areas contributing to heat loss and material testing of brick, mortar, concrete, and soil.

As a result, the following components were reviewed and rehabilitated to enhance the service life of the building:

- Site work
- Building envelope
- Lateral stability of exterior masonry walls
- Exercise Yard sliding security gate
- Security escape barriers
- Mechanical ventilation system

Site Work

Problems with site conditions around the building led to premature deterioration of the paved areas and building foundations. Poorly graded material and very poor site drainage, resulting in an accumulation of moisture in the soil and causing frost heaving of paved surfaces, were identified as the primary causes of this pavement deterioration. Further, the site grades resulted in surface drainage against the foundation walls and brick veneer, causing deterioration of the lower brick courses. The condition of the site before the remedial work is shown on Figure 2 and Figure 3.

The new site design incorporated proper drainage of the sub-base, properly specified and placed granular materials and adequate surface drainage. The grade adjacent to the building was lowered and sloped away from the foundation wall in order to drain water away from the building. Storm water management was also included. The retrofitted site work is shown on Figure 4.

Building Envelope

The exterior walls of the building were originally constructed in the following manner: concrete brick exterior wythe, air space, insulation and concrete block interior wythe. Inspection of the

walls revealed that approximately 50% of the wall system was constructed with no masonry ties or improperly installed masonry ties which were ineffective. Other deficiencies included a lack of air/vapour barrier, missing or improperly installed through-wall flashing at the base of the masonry walls, weep holes at the base of the walls which were plugged with mortar droppings and inadequate spacing of control joints. Furthermore, accumulation of moisture in the cavity walls resulting from lack of an air/vapour barrier, ineffective ventilation of the wall cavity and deficient masonry ties significantly contributed to the masonry deterioration. The typical wall section before restoration is shown on Figure 6.

Solutions were devised to increase the cavity wall's service life and to improve the overall durability of the building.

Restoration of the exterior cavity walls involved removal of the existing brick veneer and insulation and installation of a new air/vapour barrier torch applied to the block back-up wall, new insulation, new stainless steel masonry ties and new clay brick veneer. Flashing and control joint details consistent with current code and industry standards were developed and constructed. Stainless steel masonry ties were used as opposed to galvanized steel ties to suit the severe climate of Northern Ontario in accordance with the requirements of CSA Standard S478-95 regarding the effect of environmental conditions on the design service life of building components. Mortar dropping control devices were utilized during re-construction of the brick veneer to ensure that the cavity between the brick veneer and block back-up wall would be free of mortar droppings. Quality assurance was maintained during the retrofit work to verify that the wall re-construction was carried out in accordance with the design and details. A typical wall section after restoration is shown on Figure 6.

Lateral Stability of Exterior Masonry Walls

As originally constructed, the hollow core precast concrete roof slabs were not properly anchored to the masonry concrete block walls at several locations, contrary to Ontario Building Code requirements. A typical wall section before restoration is shown on Figure 6.

To provide a positive connection and transfer lateral wind load between the existing concrete

block walls and precast roof slab system, new anchorage was provided. New galvanized steel straps were grouted into cores of the hollow core roof slabs and anchored to walls with mechanical fasteners. During repair work, insulation plugs were placed in the cores of the slab to prevent air movement and cold bridging. This retrofit work increased both the structural stability and life expectancy of the building to original design requirements. A typical wall section after restoration is shown on Figure 6.

Exercise Yard Sliding Security Gate

A new 3.66 metre wide by 4.27 metre high opening and new sliding steel security gate was installed in the existing 6 metre high cantilevered concrete wall of the exercise yard to allow access of snow removal equipment. The new opening is shown on Figure 5.

During construction of the new opening, the reinforced concrete wall was found to be noticeably flexible under wind load. Analysis of the existing reinforced concrete wall revealed that the wall, as built, did not meet the wind load requirements of the Ontario Building Code, Part 4.

Several options of remedial wall reinforcement were evaluated, leading to the provision of a reinforced concrete stub wall at the critical section of the original wall. The new stub wall was connected to the existing wall and footing by drilling and grouting steel dowels. The condition before and after the repair work is shown on Figure 7 and Figure 8. The repair work provided the wall with the required strength to resist wind loads and ensure long-term durability.

Security Escape Barriers

During the early stages of rehabilitation, it was intended that the original cracked fibreglass escape barriers would be repaired and reinstalled with proper anchorage to the newly restored walls.

However, when the barriers were removed, close examination revealed that the original escape barriers were extensively degraded by ultraviolet rays. A poor quality cover coat on the fibreglass surface had resulted in moisture penetration and premature cracking of the fibreglass. The original fibreglass units were severely deteriorated, reducing their life expectancy to a few years.

The condition of a typical unit before restoration is shown on Figure 9.

Several cost alternatives were evaluated. As a result, a decision was made to provide new fibreglass escape barriers at the exercise yard and to install galvanized steel mesh security screens above the patios.

The new escape barriers have been thoroughly engineered, constructed and installed for long-term service, thereby increasing their life expectancy to 20 years. The new escape barriers are shown on Figure 10 and Figure 11.

Mechanical Ventilation System

The building's existing ventilation system was reviewed after the failure of the exhaust fans in the spring of 1996. Air quality concerns related to an insufficient outside air supply had also been reported by building occupants in the past.

As a result of a review of the operation and quality of the exhaust fans, several modifications to the existing ventilation system were recommended. The repair work improved the performance, energy efficiency and life expectancy of the ventilation system.

Summary

This project provides a classic example of the deficiencies and rapid deterioration of building components which can result from a substandard quality audit during the construction stage. Problems with materials and workmanship degraded the durability of the entire facility. Proper quality control during construction would have eliminated the costly reconstruction work that was required to upgrade the building to its original design service life condition. Adherence to CSA Standard S478-95 would have prevented these construction quality problems from occurring. The standard provides for the implementation of a quality management program to ensure that proper checks are made and corrective actions are taken so that the building and its components meet performance expectations over the design service life.

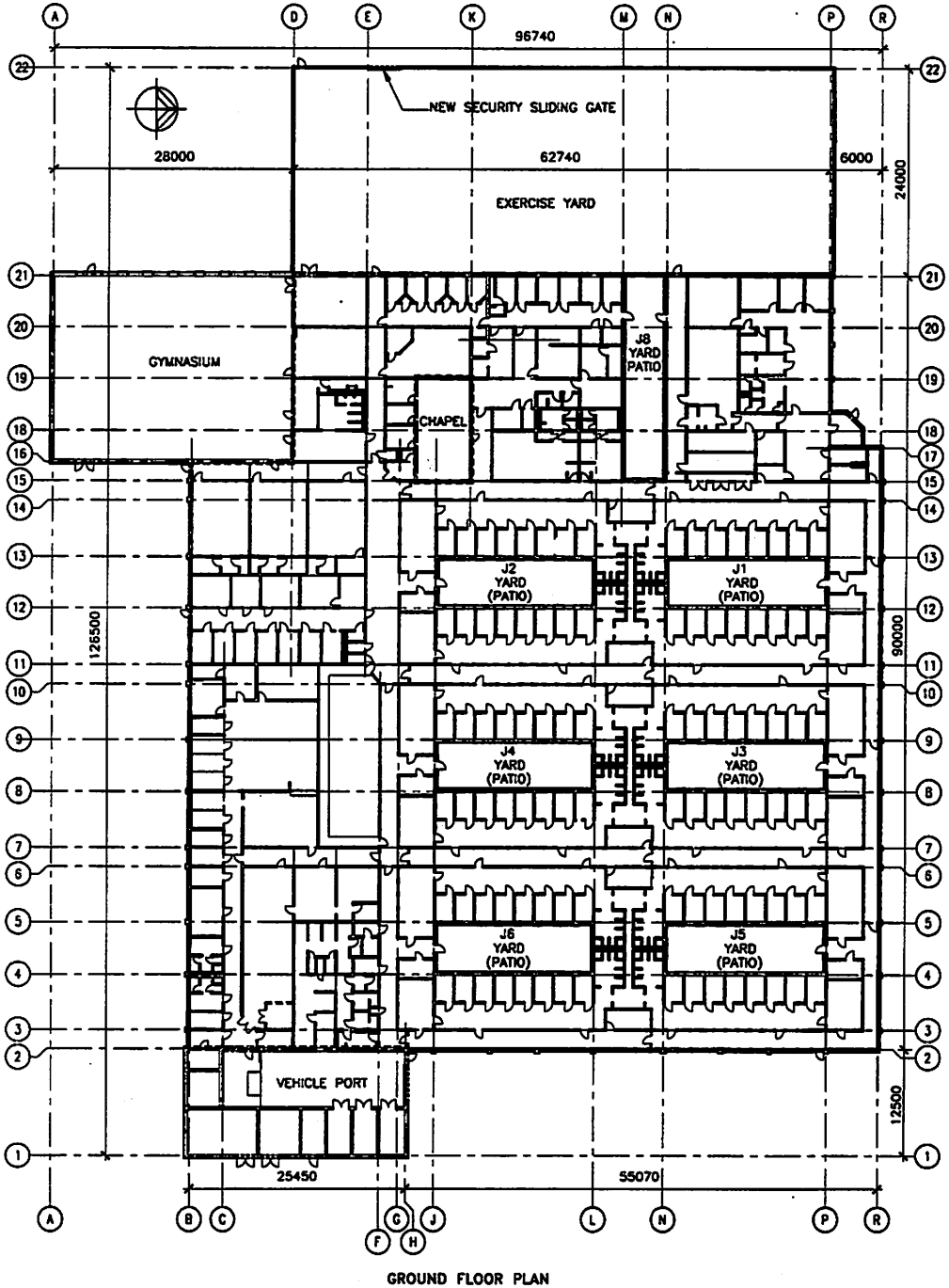


Fig. 1 Building Layout

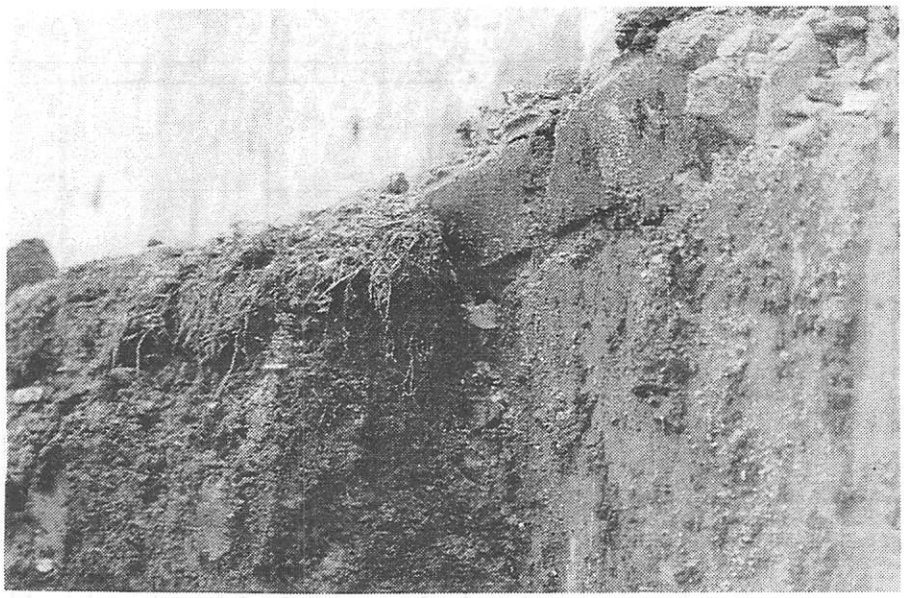


Fig. 2 Existing ground elevation higher than foundation wall at west elevation - typical all around building.

Fig. 3 South parking showing extensive heaving and cracking in asphalt. Part of the roadway has caved in.

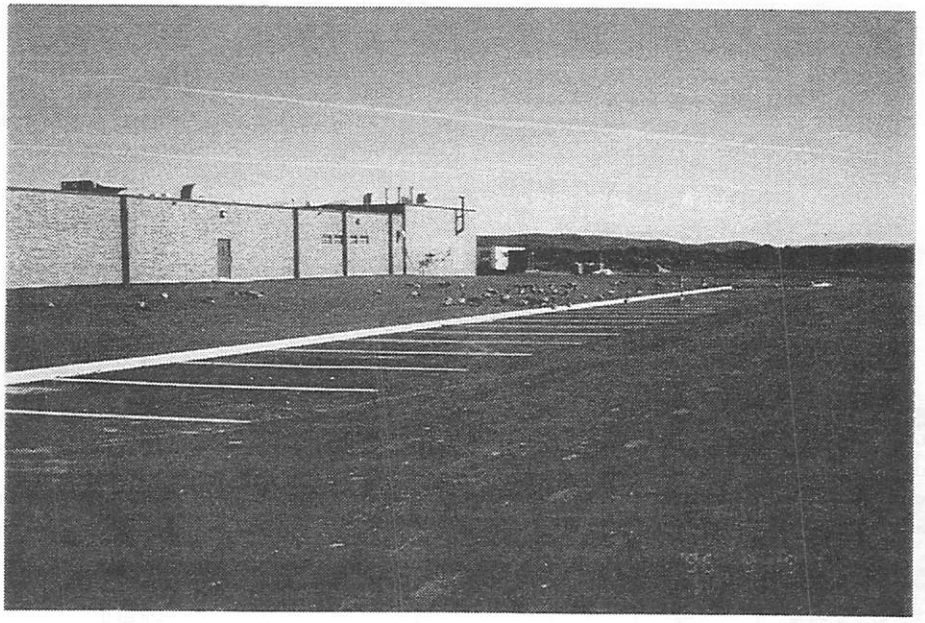


Fig. 4 Completed site work at south elevation.

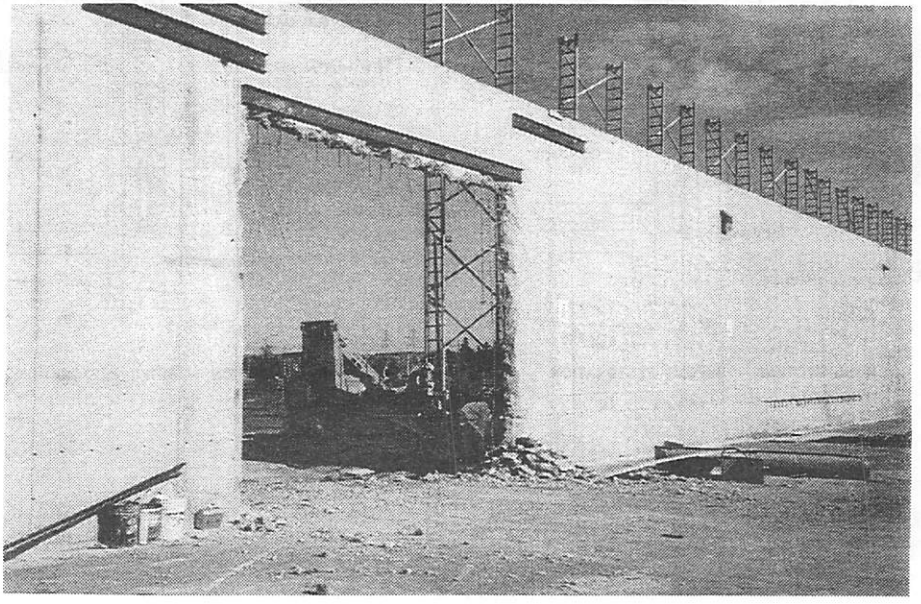
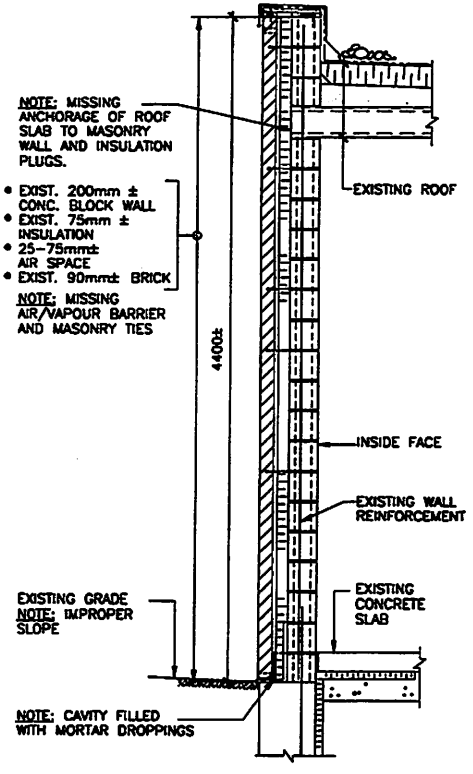
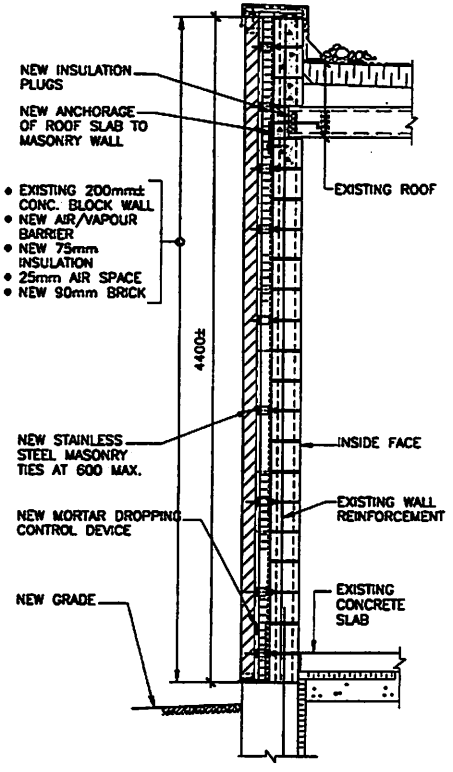


Fig. 5 Enlarged opening into exercise yard for new sliding gate.



WALL SECTION – BEFORE RESTORATION



WALL SECTION – AFTER RESTORATION

Fig. 6 Masonry Wall Sections

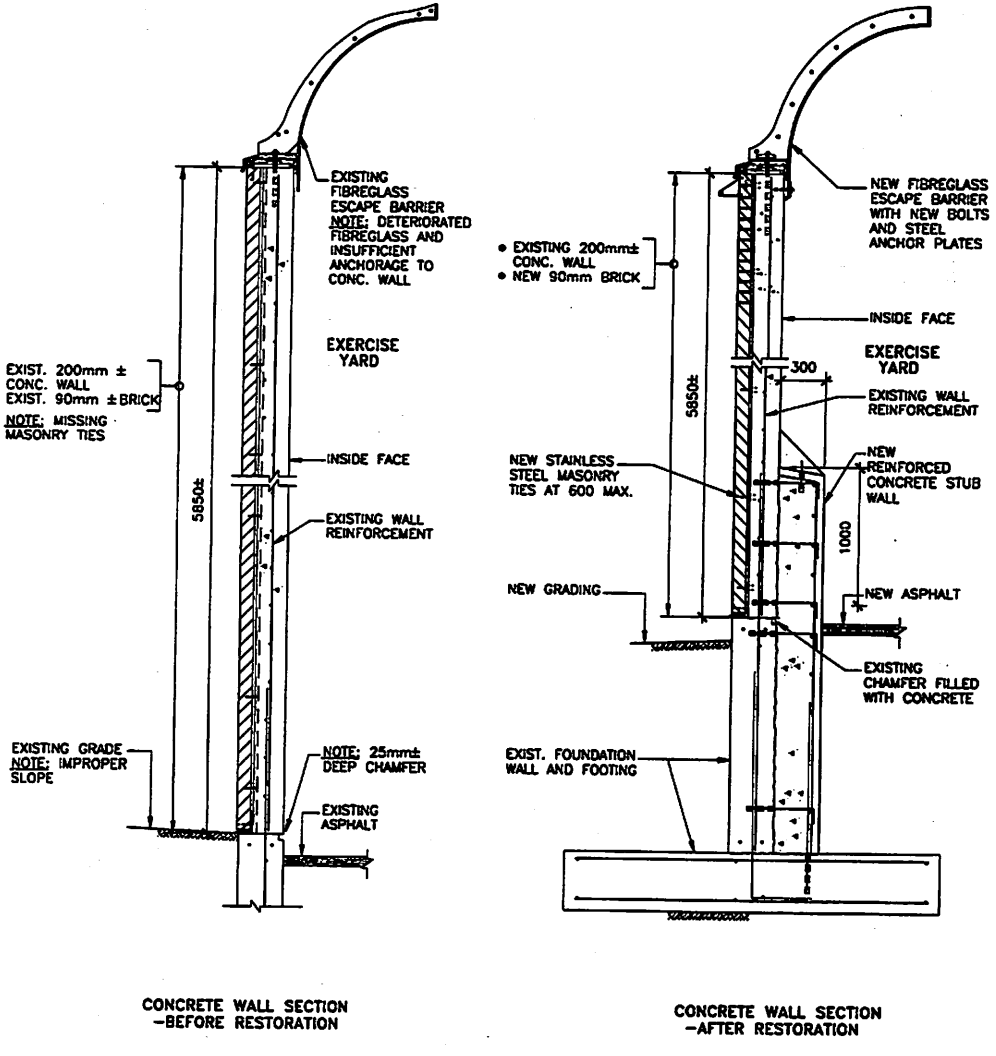


Fig. 7 Concrete Wall Sections

Fig. 8 Imported granular 'B' backfill being placed and compacted at new reinforcing wall in exercise yard..

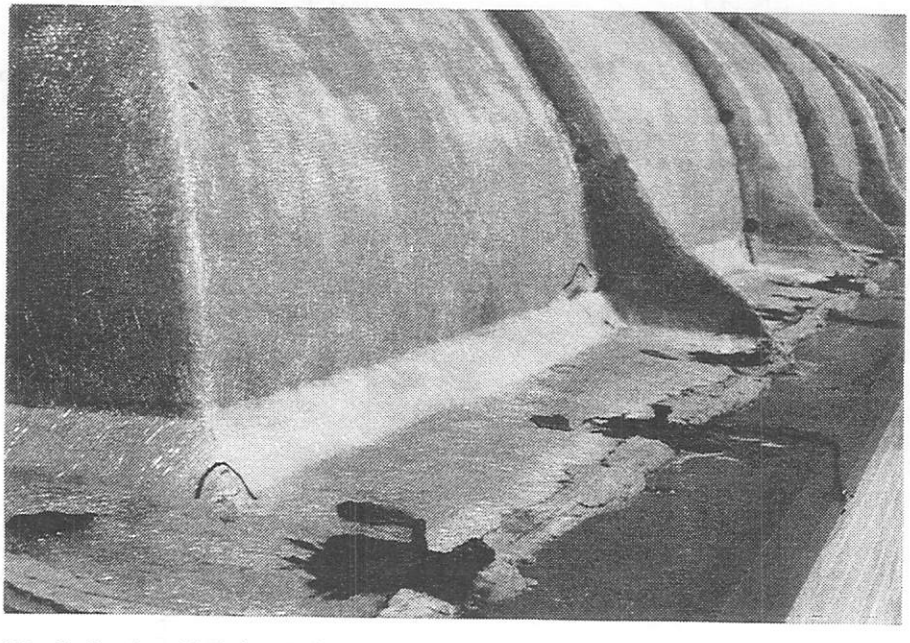


Fig. 9 Crack and hole in panel.

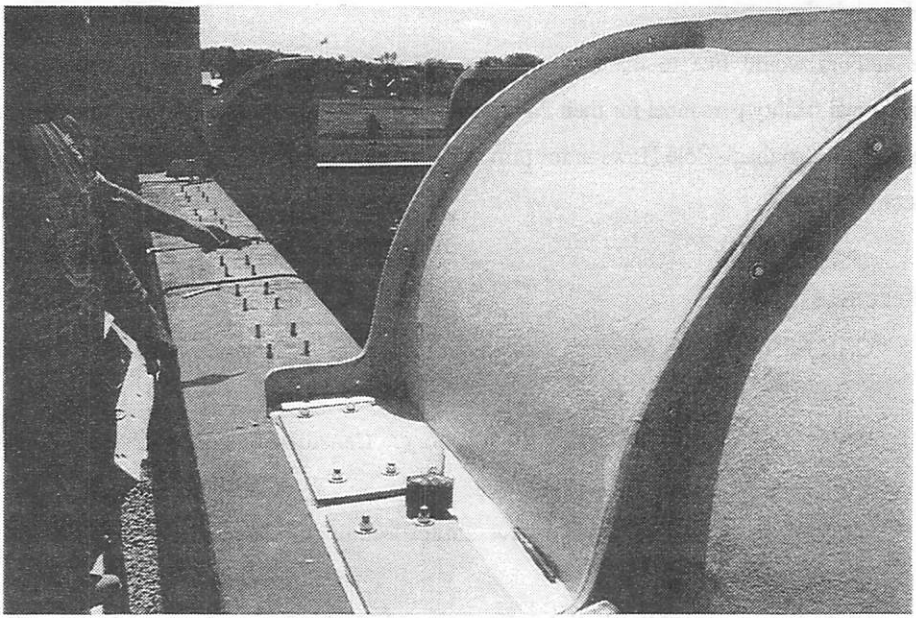


Fig. 10 Quality control-PolyGauge checking part thickness.

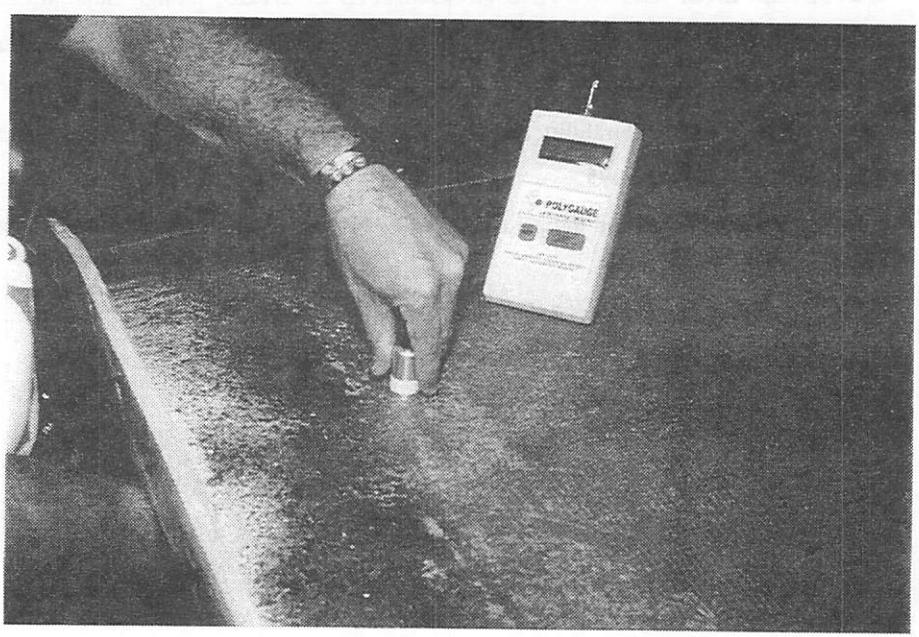


Fig. 11 Fibreglass escape barriers being installed at column line 21 of the exercise yard..

Acknowledgement

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Basement System Performance Assessment

Ted Kesik[1]

Abstract

The *basement as a system* concept implies the need for comprehensively assessing system performance. Residential basements in new housing are now fully expected by consumers to potentially perform as habitable spaces, offering the same quality environment as the rest of the dwelling. Based on numerous studies, and the reporting of defects by new home warranty organizations, the conventional, *"inherited"* technologies for basements do not consistently deliver the expected level of performance.

Prescriptive code requirements for basements permit many combinations of sub-systems, components and materials which may be incompatible and/or fail to address all performance parameters effectively. As new components and materials are introduced, the probability of over or under-designing basements increases within the context of prescriptive codes and standards. Objective-based codes linked to performance parameters are considered more appropriate within a global marketplace of building technologies, however, before these may be implemented, a comprehensive framework of performance parameters must be established.

A key consideration involves the presentation of performance assessment data, particularly of an economic nature, in formats that are useful to all stakeholders, namely, manufacturers, designers, builders, regulatory officials and consumers. This paper deals with the major initiatives, challenges, issues and opportunities that are associated with the standardization of basement system performance assessment.

Keywords: basement system, performance assessment, life cycle analysis, residential basement system performance standard

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Basement System Performance Assessment

Ted Kesik

Introduction

It has been recognized that building technology is rapidly moving away from evolved "trial and error" approaches which are encapsulated in prescriptive codes and standards, towards "performance-based design" approaches. A successful transition will likely require an explicit and comprehensive means of assessing acceptable performance for systems which do not conform with any past precedents of building technology. This paper is intended to provide an overview of the initiatives, challenges, issues and opportunities associated with the adoption of an objective-based approach to residential basement systems.

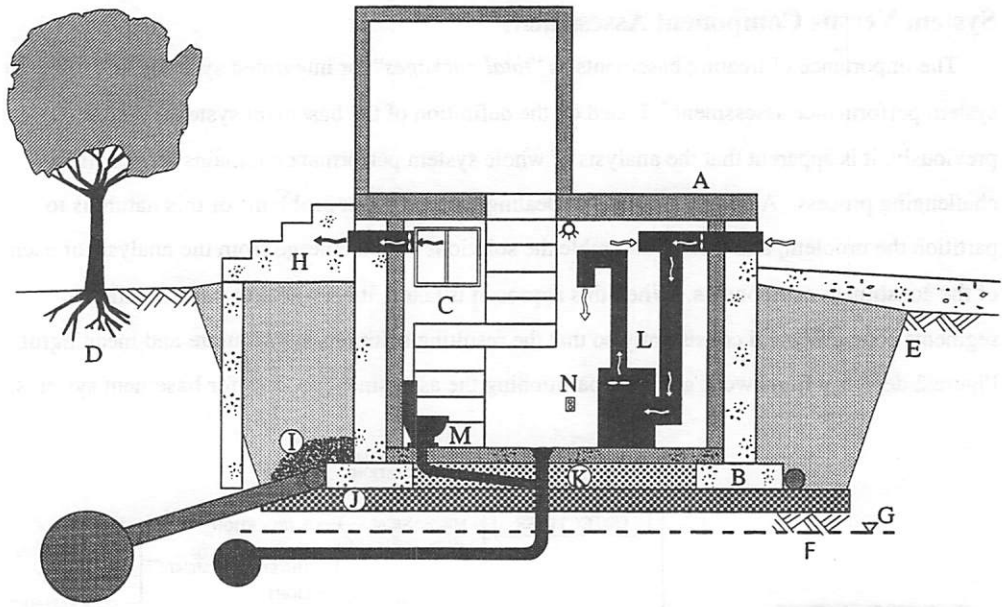
Definition of the Basement System

Before any assessment of the basement system may be performed, the basement system must first be defined. The definition provided below is based on past research in this area.[1]

The basement system comprises a building space with some portion of the envelope in contact with soils and/or rock and includes:

- *the structural elements and building envelope which support and enclose the space, including interior finishes and any attached structures;*
- *all access and egress, including fire separations, operable windows and resistance to forced entry;*
- *the native soil and its groundwater table, all backfill and adjacent soils, including the site materials and their grading, landscaping and plants;*
- *the foundation drainage system including weeping tiles, granular drainage layers, sewers, sumps, ditches and drywells; and*
- *the mechanical services including plumbing (potable water supply and sanitary drainage), heating, ventilation and air conditioning systems; and*
- *the electrical/lighting systems including alarms, sensors and telecommunications.*

Figure 1 depicts a generalized working definition of the basement system, revealing the complexity of relationships involved in the performance of residential basements.



A BUILDING ENVELOPE ENCLOSING THE BASEMENT SPACE
B STRUCTURAL ELEMENTS (FOOTINGS, FOUNDATION WALLS, ETC.)
C ACCESS/EGRESS INCLUDING FIRE SEPARATIONS AND OPERABLE WINDOWS
D PLANTS AND LANDSCAPING
E BACKFILL INCLUDING DISTURBED SOIL AND SITE GRADING
F NATIVE SOIL AND/OR ROCK
G GROUNDWATER TABLE
H ATTACHED STRUCTURES (STAIRS, PORCHES, GARAGES, ETC.)
I FOUNDATION DRAINAGE (MUNICIPAL SEWER, SUMP PUMP OR GRAVITY)
J GRANULAR DRAINAGE LAYER
K SUB-SLAB GRANULAR MATERIAL
L HEATING, VENTILATION AND AIR CONDITIONING SYSTEMS
M SANITARY PLUMBING
N ELECTRICAL/LIGHTING, ALARMS, SENSORS, TELECOMMUNICATIONS

Figure 1 - Working Definition of the Basement System

Basement as a System Performance

Aside from its complexity, the performance of basement systems continues to draw considerable interest within the residential construction industry for the following reasons:

1. Consumer expectations for the performance of basements as potentially liveable spaces, have placed increasing demands on standards of building technology;
2. The recognition of the need to take a systems approach to basements, within the context of objective-based codes, has initiated renewed interest among building scientists;
3. The availability of cost effective performance modelling and demonstration/validation techniques has reduced the cost and time needed to refine acceptable prototypes; and
4. There are significant opportunities for all stakeholders which may be realized by moving toward rationalized basement systems.

System Versus Component Assessment

The importance of treating basements as "*total packages*", or integrated systems, is the key to system performance assessment.[†] Based on the definition of the basement system noted previously, it is apparent that the analysis of whole system performance remains an extremely challenging process. A common means of dealing with complex problems of this nature is to partition the problem, and then to assemble the solutions which emerge from the analysis of each of the constituent components. When this approach is taken, it is critical to partition the segments coherently and consistently so that the resulting solutions are accurate and meaningful. Figure 2 depicts a framework aimed at partitioning the assessment process for basement systems.

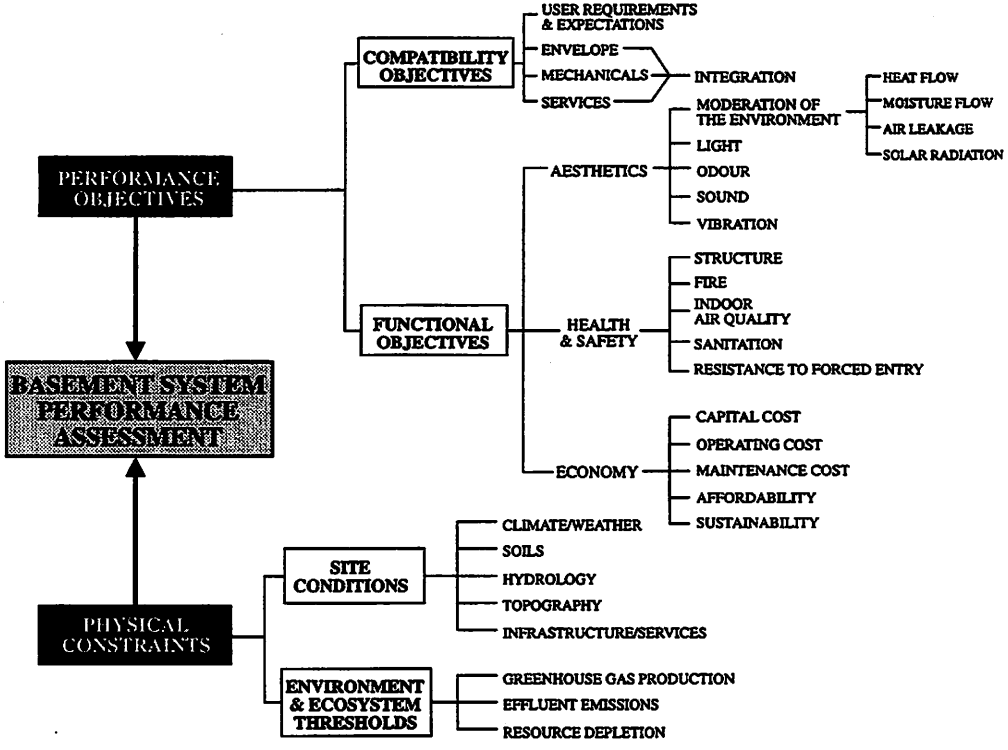


Figure 2 - Basement System Performance Assessment Framework

[†] This was a major conclusion of the *Ryerson/NRCC Workshop on Developing Performance Objectives for Basements*, held on March 28, 1996 at Ryerson Polytechnic University.

The need to formalize the basement system performance assessment process is reinforced by reviewing the documents referenced in the *National Building Code of Canada 1995*. Of the 255 codes and standards listed, only a handful deal with system performance concepts - none of these are related to basements. It appears that modern building science has predominantly focused on the first three areas of the building performance assessment process depicted in Figure 3.

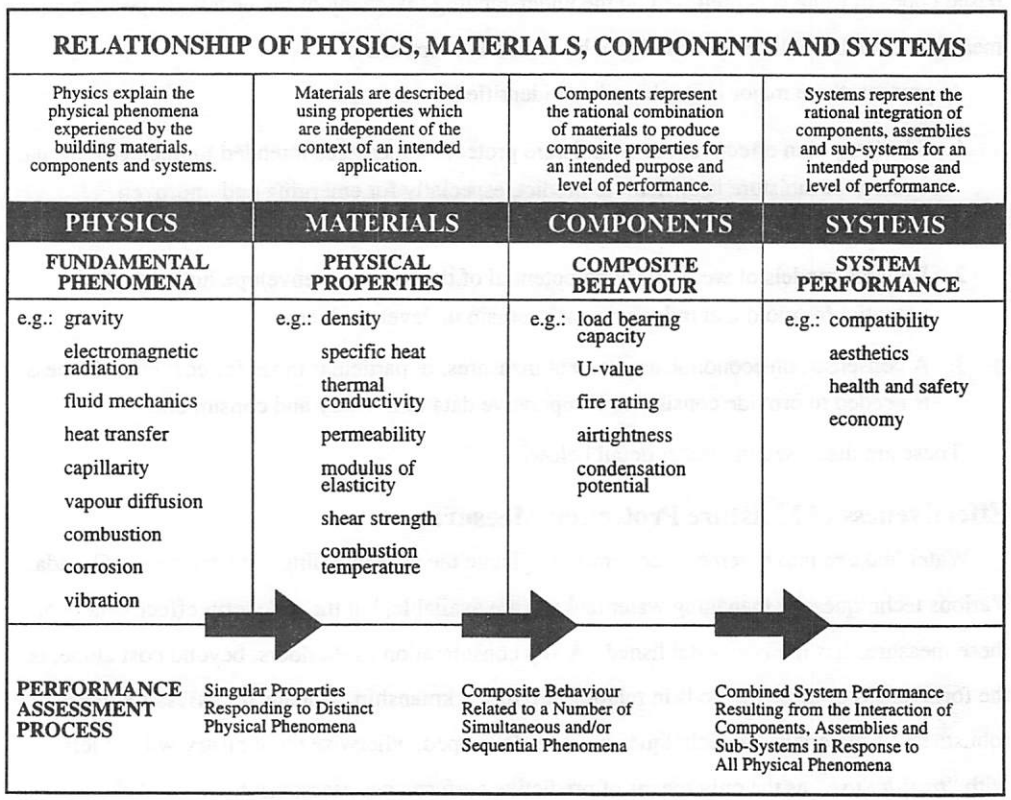


Figure 3 - Building System Performance Assessment Hierarchy

The capability to deal with whole system performance is beginning to emerge. This is due to the development of sophisticated technologies which include computer simulation/modelling of physical behaviour, and knowledge based expert systems. Unexpectedly, these technologies have advanced beyond our consensus on relevant performance parameters and assessment criteria. They represent powerful tools in search of integrative tasks. The following section highlights a number of challenges which remain to be addressed before further work may progress.

Critical Issues

Despite considerable advances in building science, a number of critical issues with respect to basement system performance need to be resolved. A consensus is needed so that consistent yardsticks of performance are used within the industry. This realization should not diminish the tremendous progress which has been evidenced to date. The announced move towards objective-based codes in Canada is premised on the understanding that many of the necessary performance measures have been developed, and will be available to industry.[2]

At present, three major issues have been identified:

1. The long term effectiveness of moisture protection measures intended to manage external sources of moisture is difficult to predict, especially for emerging and unproven technologies (i.e., drainage membranes);
2. Reliable models of wetting/drying potential of the basement envelope linked to the potential for mold and mildew growth remain undeveloped; and
3. A consensus on economic assessment measures, in particular those for cost effectiveness, is needed to provide consistent, comparative data to industry and consumers.

These are discussed in greater detail below.

Effectiveness of Moisture Protection Measures

Water leakage into basements continues to plague the homebuilding industry across Canada. Various techniques for managing water leakage are available, but the long term effectiveness of these measures has not been established. A key consideration for builders, beyond cost alone, is the forgiveness of these methods in relationship to workmanship. Means for assessing the robustness of materials and techniques must be developed, otherwise the industry will be left with "*trial-by-use*" as the only means of predictive performance assessment.

The plugging of foundation drainage tile within several years of installation has been reported by several new home warranty programs. This phenomenon points to the need to determine drain plugging potential, and to correlate this to appropriate foundation drainage technology. Consumers normally expect acceptable service from drainage tile for the life of the building.

Basement flooding due to municipal sewer backup is evidenced annually in urban areas across Canada. The cost and health implications of basement flooding are significant, and appropriate measures are not found within current building codes. The implications of basement

flooding extend to the occupancy of basements and their intended use. Liability issues for municipalities and builders may also prove significant. Considerable research has been carried out in this area[3,4], and effective measures must be developed and made available to builders and municipalities.

Effects of Wetting/Drying on Molds and Mildew

The physics explaining the wetting/drying potential of basements is well developed.[5] Evidence to date supports a positive correlation between moisture, molds and mildew in houses (primarily basements) and adverse health effects in occupants.[6] Chronic wetting due to condensation of basements which are finished on the interior can be predicted through computer simulation. The correlation of simulation data to observed performance in the field needs to be conducted in order that the predictive assessment of wetting/drying potential and mold/mildew formation potential is available to designers. Based on research conducted to date, the quantity and arrangement of thermal insulation, and the means to control water vapour migration so as to avoid prolonged periods of condensation are important considerations. The chronic wetting of basements due to water leakage, sewer backup or flooding are additional and equally important considerations. The cost differences which arise between basement systems attributable to how they manage mold and mildew formation may be compared once an adequate performance model of control is available.

Appropriate Measures of Cost Effectiveness

The cost effectiveness of high performance basement technology remains to be determined. A number of economic assessment measures are available to evaluate the cost effectiveness of alternative basement systems and materials. These range from straightforward methods such as simple payback (PB) to more complex methods such as savings to investment ratios (SIR), adjusted internal rate of return (AIRR) and life cycle cost (LCC) analysis.

Each measure has limitations which make it better suited to some types of economic decisions versus others. All of the methods reflect an elementary decision rule:

No rational person is expected to undertake actions where anticipated costs exceed anticipated benefits.[7]

The challenge for decision-makers is to appropriately assess the anticipated costs and benefits. Fortunately, a great deal of work has been performed in this area, and a widely accepted approach to selecting appropriate measures for the assessment of building technology exists.[8]

Life Cycle Versus Alternative Cost Effectiveness Measures

Where whole system assessment is required, life cycle cost (LCC) approaches are often preferred over other measures. This method is particularly well suited to making decisions regarding the design or size of components and systems. Life cycle cost/benefit measures provide a comparison between the performance of competing alternatives. This comparison is typically expressed as a present value of the costs and benefits over the service life of an investment. The present value is normally calculated using the time-value of money based on selected discount and escalation rates. The lowest life cycle cost usually represents the most cost effective alternative, all other considerations being equal.

Life cycle assessment is highly appropriate when considering alternative means of attaining minimum levels of health and safety in buildings, and for optimizing the size (i.e., strength, thermal resistance, etc.) of components and sub-systems. It is not as well suited to all of the business and consumer aspects of building technology. Typically, builders engaged in the business of construction are not interested in the life cycles of their products, which statistically far exceed the average life of a contracting firm. Consumers of buildings (landlords, tenants and owner-occupants) tend to be most interested in affordability during the period of their tenancy, and in particular during the initial few years. Alternative measures which reflect these perspectives are available, however, these must be properly applied according to their assumptions and limitations. Issues of stakeholder perspectives and related economic factors are discussed in the section which follows.

Economic Perspectives: Builders, Consumers and Society

The various perspectives that are brought to bear on investments in building technology require careful consideration if the results obtained from analyses are to prove useful to stakeholders. For buildings in general, including residential basements, there exist three major perspectives to be considered: builders; consumers (owners and tenants); and society.[9]

Builders and/or developers, are primarily concerned with first costs and how these affect their business operations. The tendency by builders to avoid exceeding minimum Code requirements

is most evident when the benefit is not visible (e.g., thermal insulation, drainage layers, etc.) as opposed to highly visible amenities (e.g., upgrades to fixtures and finishes, etc.). The carrying costs and opportunity costs associated with higher first costs must result in substantial benefits, both short term (marketability) and long term (reduced callbacks and complaints), if builders are to elect better practices.[10]

Consumers of housing are generally more interested in affordability and accessibility.[11] Accessibility, as it relates to the financial capacity of potential homebuyers, primarily relates to mortgage policies and methods employed by financial institutions who finance housing purchases. Affordability relates the cost of securing adequate housing at a cost which does not place an unreasonable financial burden on a household. It involves the downpayment and monthly expenditures on principal, interest, taxes and energy (PITE). Insurance premiums may also prove significant depending on the risk of damages associated with a potential dwelling (e.g., basement flooding, etc.). Consumers are generally averse to improvements in housing which negatively impact affordability, unless these arise in response to matters of health and safety.

The societal perspective on investments in building technology is generally long term, taken over the useful life of the dwelling. The primary concern is the viability of the housing over its life cycle and how to maximize this benefit across all of society. Economic repercussions, environmental impacts and quality of life are some of the issues which take on a societal importance with respect to building technology.

Keeping in mind these three, related perspectives, this paper now continues with a discussion of additional factors to be considered when performing assessments of cost effectiveness.

Study Periods, Discount Rates and Escalation Rates

Study periods, escalation rates and inflation rates are key factors affecting the outcome of life cycle cost-benefit analyses. These are often problematic for decision makers due to their lack of predictability. When a basement system, as defined earlier in this paper, is evaluated, there will be various service lives associated with the sub-systems and components. The discount rates for mortgages versus personal loans are often substantially different, hence financing a replacement furnace or defect repair has to be analyzed separately from investments in technology which are carried by the mortgage. Inflation rates, and especially escalation rates for purchased energy, are

highly subject to variability. The discussion which follows highlights some of the means available for dealing with these factors.

When LCC [life cycle cost] analyses of alternative building systems or design practices are performed for general information rather than for a specific application, (for example, government or industry research to determine the cost effectiveness of thermal insulation or high-efficiency heating and cooling equipment in typical installations), the study period will often coincide with the service life of the material or system (but be limited to the typical life of the type of building where it is to be installed). When the service life is very long, a more conservative choice for the study period might be used if the uncertainty associated with the long-term forecasting of costs substantially reduces the credibility of the results.[12]

For most recent life cycle analyses of housing technology performed in Canada, the study period has ranged from 25 to 30 years, corresponding to the typical length of a mortgage, and the typical length of tenure for a household in a dwelling without major renovation or retrofit, respectively.[13] For basements, the study period for items such as the structural elements may be set at 50 to 75 years, or more. This study period may also apply to foundation drainage systems and buried services. For major space conditioning appliances, and items such as interior finishes, a 15 to 20 year study period may prove more appropriate. The study period will tend to be shorter when the builder and consumer perspectives are assumed, and longer when a societal perspective is taken.

Discount (interest) and escalation rates are normally set at current levels, and projected ahead over the study period as constants, or exponentiated (inflated or deflated) according to a particular economic scenario. It is important to appreciate the importance of selecting meaningful interest and escalation rates. Figure 4 illustrates the sensitivity of the present value of savings to the study period, discount and escalation rates. Using energy savings as an example, the cost effectiveness of energy saving measures declines as interest rates increase, provided the escalation rate for energy prices remains below the interest rate. On the other hand, an escalating future energy price scenario, where the escalation rate exceeds the discount rate, leads to an increased estimate of cost effectiveness for energy saving measures. Escalation rates vary between items such as energy, materials and labour, and these variations are usually treated by performing sensitivity analysis or applying mathematical techniques for dealing with uncertainty.

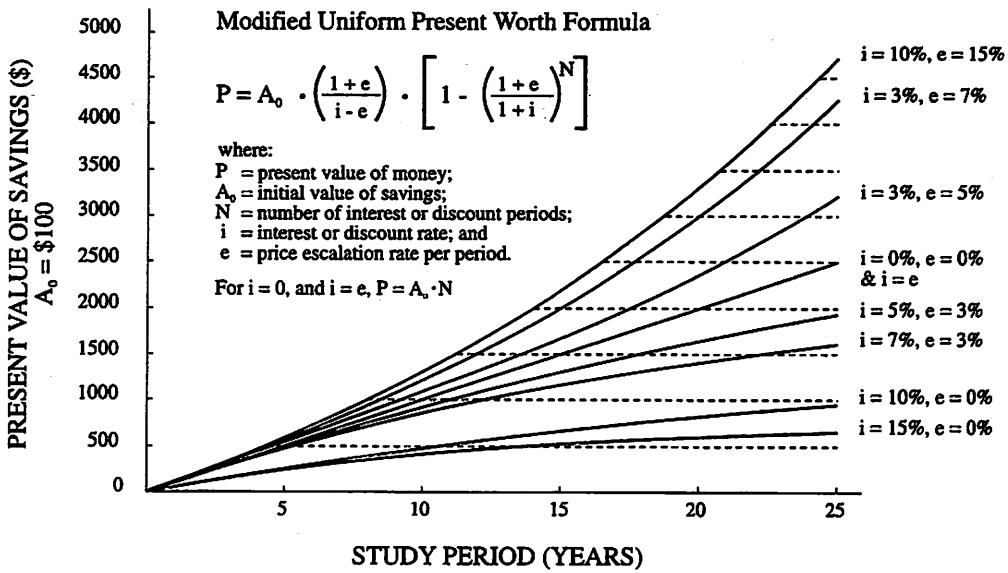


Figure 4 - Sensitivity of Present Value Savings to Study Period, Discount Rates and Escalation Rates *(adapted from Fig. 3, ASTM E917-93)*

There are additional considerations, both economic and intangible, which must be monetized before comparative information can be provided to industry and consumers. These have been identified as:

- Reliable data for construction, operating, maintenance and repair of basement systems is needed to perform accurate economic analyses, especially over the life cycle.
- Externalities and opportunity costs associated with various basement systems must be considered to balance societal concerns with builders' sensitivity to first costs.
- Comfort, compatibility and adaptability of basement systems must be monetized to reflect the benefits associated with high performance basement technology.

When these considerations have been resolved, consistent economic assessments may be conducted and communicated to stakeholders. Table 1 indicates the recommended measures for assessing the cost effectiveness of basement technology.

Table 1 - Recommended Study Periods and Economic Measures for Assessing the Cost Effectiveness of Basement Technology

Perspective	*Investment or Improvement*	*Recommended Study Period*	*Recommended Economic Measure*
Builder	Technology exceeding minimum health and safety requirements	Commencement of construction to time of sale (< 1 year, typical)	Adjusted Internal Rate of Return (AIRR)
Consumer	Discretionary, depreciable and non-depreciable improvements	Expected period for benefits to exceed costs (5 to 10 years)	Simple Payback (PB) or AIRR
	Non-discretionary, depreciable investments	Useful service life of investment	Life Cycle Cost (LCC) using Uniform Present Worth (UPW)
	Non-discretionary, non-depreciable investments	Duration of tenure or mortgage (25 to 40 years)	Life Cycle Cost (LCC) using Uniform Present Worth (UPW)
Societal	All investments	Service life of system, including components, equipment, fixtures and finishes (50 to 100 years)	Life Cycle Cost (LCC) using Modified Uniform Present Worth (MUPW)

The term *discretionary improvements* refer to any measures which exceed minimum requirements for health and safety, whereas *non-discretionary investments* refer to any available measures needed to comply with minimum requirements for health and safety. From a consumer perspective, a *depreciable* item is one with a service life which is less than the duration of tenure or mortgage, whereas a *non-depreciable* item does not significantly depreciate during this period.

Current Activities

There are a number of initiatives regarding basement system technology which are underway in Canada. Many of these are of a proprietary nature, and hence may not be presented within this paper. However, a large number of government and industry related initiatives have been recently coordinated to substantially advance residential basement performance within the *Performance Guidelines for Basement Envelope Systems and Materials Project*. The Institute for Research in Construction at the National Research Council Canada is planning the development of guidelines for the design and evaluation of basement envelope systems and materials. The *Basement Guidelines Project* is being carried out in three phases:

Phase 1: Overview of the building physics, review of related codes and standards, and development of an outline of the guidelines.

Phase 2: Laboratory (testing and computer simulation) and field performance evaluations of basement envelope systems and materials, and the development of a communication plan.

Phase 3: Cost-benefit analysis and demonstration of recommended approaches, development of the final draft of the guidelines, and the implementation and communication of the guidelines.

Approximately 2 years hence, at the conclusion of this project, the framework for designing and constructing integrated basement systems will be made available to industry. This is expected to lead to significant opportunities.

Opportunities

The transition from basements which are assembled by selecting methods and materials permitted within prescriptive building codes, to basements which are integrated using rational performance parameters, holds numerous opportunities for all stakeholders.

The buildability and marketability of high performance basements hinges on the assumption that basement technology will move towards a *"systems"* approach. This approach will be similar to that taken by equipment and appliance manufactures who integrate sources of components and materials in their products. In the case of basement technology, one future scenario predicts that products and material manufacturers will work in concert to develop basement systems that conform with minimum levels of health and safety, and consumer expectations. It may also be assumed that market forces will lead to cost effective alternatives for consumers. Builders may have to become, or hire, certified system installers which are capable of constructing the basement system in accordance with manufacturer's certified installation instructions.

From the manufacturers' perspective, the expert diligence in design ensures systems which comply with minimum requirements and expectations. From the builders' perspective, technical support, training and quality control by the manufacturer make basements practically as reliable and straightforward as furnaces. From the consumers' perspective, the delivery of the product is familiar (engineered, integrated package similar to household equipment and appliances), the

warranty is backed by a relatively stable manufacturer or consortium of manufacturers, and there will be readily available means of comparing among products through advertisements, and possibly consumer reports.

Many builders advertise the use of brand-name equipment, components, fixtures and finishes in their new homes. High performance basements, like high performance windows, will take some time to research, develop and demonstrate. It is hypothesized that *"packaged systems"* may enjoy a considerable market advantage over systems which are assembled by builders using presently permissible combinations of materials and components. Evidence to date suggests that many of today's builder-selected basements represent combinations of materials and components which individually comply with minimum requirements for health and safety, but frequently fail to meet consumer expectations.

It is being suggested here that workmanship and marketability will tend to become the responsibility of manufacturers and product suppliers who are interested in having their materials and components associated with well performing basements.

Conclusions

The future directions for basement system technology are numerous and positive. Some of these are highlighted as follows:

1. A basement system standard, developed along the same lines as *CAN/CSA-A440, Windows*, will formalize the performance requirements and criteria for basement systems. Advances in technology will be integrated on an ongoing basis through the standard development process;
2. The development of basement system design assessment checklists, derived from a performance standard, and coupled to objective-based codes, will enable designers/manufacturers to rationally integrate well performing systems;
3. Performance rating reports will provide consumers and builders with consistently derived information permitting comparison and objective decision making; and
4. The potential for export of Canadian basement technology will be enhanced by systems which meet or exceed international standards of performance and quality assurance.

Basement system performance assessment offers the building science field a unique opportunity to embark on a path to the advancement and implementation of objective-based codes from the ground up.

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[13] Refer *to Energy Impact and Cost Effectiveness of Energy Efficiency Improvements in Housing in Ontario*, prepared by Habitechnica for The Ontario Ministry of Energy, 1991, and also, *Specification for Calculation Procedures for Life Cycle Cost Analysis for the Canadian Code for Energy Efficiency in New Houses*, Canadian Commission on Building and Fire Codes, National Research Council of Canada, Ottawa, 1993.

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Monitoring of the Building Envelope of a Heritage House - A Case Study

M.N.A. Saïd[1], W.C. Brown[1], C.J. Shirtliffe[1] and A.H.P. Maurenbrecher[1]

Abstract

The paper describes the long-term monitoring of the hygrothermal performance of the building envelope of a heritage house located in Ottawa. The house, once the residence of two of Canada's Prime Ministers, now serves as a museum. To preserve the historical artifacts within the building, the specified temperature and relative humidity for the indoor air are 21°C and 35% to 50% respectively. As the house must also be preserved, there was concern about the effect of the high indoor relative humidity (moisture) on the durability of the building structure. The main objective of the monitoring was to assess the effect of the conditioned air on the building envelope.

Selected wall sections and a window were continuously monitored from March 1995 to August 1996. The monitoring included indoor and outdoor conditions and the attic environment. Temperature, relative humidity, surface wetting-drying cycles (from precipitation or condensation), and air pressure differential were monitored. This paper describes the monitoring approach and results.

The results indicated that the brick walls are unlikely to experience internal condensation problems as long as they are subjected to negative air pressure difference. However, because the building is quite leaky, the negative pressure introduced too much cold dry air from the exterior. It caused localized cold spots with condensation and ice formation on interior of walls and ceiling. Negative air pressures difference are not a solution unless the leakage paths are reduced

Keywords: thermal, moisture, building envelope, monitoring, heritage house, masonry

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Introduction

The paper describes the long-term monitoring of the hygrothermal performance of the building envelope of a heritage house (Laurier House) located in Ottawa. The house, once the residence of Prime Ministers Laurier and King, now serves as a museum (Fig. 1). To preserve the historical artifacts within the building, the indoor air conditions specified are a temperature of 21°C, and a relative humidity (RH) of 35% (dew-point 5°C) in the winter and 50% (dew-point 10°C) in the summer. It is also desirable that short-term (daily) variations in RH are no greater than 5%. High humidity can compromise the life of the building envelope and artifacts.

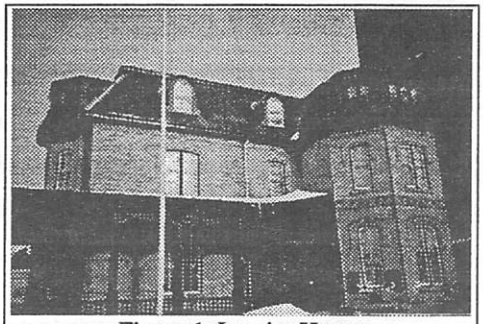

Figure 1 Laurier House

A preliminary study of selected windows and walls indicated that both the single windows and windows with storm windows can have significant condensation at outdoor temperatures below -10°C when interior conditions are maintained at 21°C and 35% RH [1]. The study recommended additional long-term monitoring which would include walls. Before the HVAC system was upgraded in 1993, hygrothermograph readings over the period January-February 1991 indicated a range of 5% to 10% RH and approximately 24°C indoor conditions (dew-point -19°C to -10°C). In the February-March 1993 preliminary monitoring, indoor conditions were 20% to 30% RH and 23°C (dew-point -1°C to 4.5°C). A long-term monitoring investigation from March 1995 to August 1996 was initiated to assess the effect of the addition of conditioned air on the building envelope. The investigation also included a thermographic survey of the exterior of the building and an air leakage test of the entire building. This paper describes the instrumentation used in the monitoring program and examples of results.

Building Description

The house, built in 1878, is a three storey building with an uninsulated full basement. A two storey wing at the rear was added later. Major renovations were carried out in 1922. The total floor area is about 650 m^2 (not including the basement). The first and second storey exterior walls are load bearing solid brick walls (330 mm thick), the third storey is enclosed by a wood frame mansard roof with the sides covered with slate tiles. The roof is insulated to approximately R-25. All walls are finished with lath and plaster on the interior. Windows are either single-glazed, double hung wood frame windows with single-glazed wood frame storm windows on the exterior; or leaded, single-glazed metal casement windows with single-glazed wood frame storm windows on the interior.

The HVAC system consists of two air-cooled indoor air-conditioning units (20 ton refrigeration total capacity), an electric reheat coil (21 kW capacity), and four electrode steam humidifiers (42 kg/h total capacity). The humidifiers are controlled by a duct humidistat. One system serves the ground floor and the southern parts of the second and third floors. The other serves the northern parts of the second and third floors. In winter, the HVAC system provides ventilation but heating is provided by existing perimeter hot water radiators with individual thermostats.

Instrumentation

Four wall sections, the attic, two foyers, a window, and an outdoor location on the site were chosen to be instrumented. Figure 2 shows cross-sections of the walls monitored and the location of the instrumentation. The window selected was a leaded single-glazed metal frame casement window (glass 6 mm thick; the storm window was absent during the monitoring because of maintenance). The window is located in the east wall of the dining room on the first floor. The preliminary study showed severe condensation was possible on the same window. The wall sections instrumented were the east wall in the drawing room on the first floor, the north wall in the dining room on the first floor, the west wall in "Mr. King's" bedroom on the second floor, and the north knee-wall on the third floor. Figure 3 shows the locations monitored on the first and second floors.

The monitoring sites were chosen from openings for previous inspection. The openings in the walls were reconstructed after the instrumentation. One exception was the north wall in the dining room, which was instrumented through an existing electric outlet. The north-facing

section of the attic (over mechanical room), the first floor foyer, and the second floor foyer were also instrumented. The parameters monitored were temperature, relative humidity, wetting-drying cycles on wall surfaces, and air pressure differential across the wall. The exterior air temperature and relative humidity were also monitored about 5 m to the east of the building at 2 m height.

Temperature: Temperature was measured using type T thermocouples (calibrated to ±0.1°C). The thermocouple wire was shielded to reduce any electrical noise caused by extensive alarm systems. For surface temperatures, the thermocouples were bonded with epoxy to the surface and covered with cloth construction tape. The thermocouple measuring exterior air temperature was protected from solar radiation by a radiation shield.

Relative humidity: Polymer resistance relative humidity (RH) sensors were used (specified accuracy ±1% and ±2%). The calibration of the RH sensors were confirmed using saturated salt solutions and in a small temperature-controlled environmental chamber.

Air pressure: Pressure transducers with two ranges were used: ±250 Pa for wall cavity-to-indoor air pressure differential and ±625 Pa for outdoor-to-indoor air pressure differential. The specified accuracy of the transducers is ±0.14% of full scale. The transducers were calibrated using a forced-balance calibrator to better than 1 Pa.

To avoid drilling through the window frames, a 3.2 mm copper tubing (1.5 mm I.D.) was installed between the shutter and the window frame. Nylon tubing (6 mm I.D.) connected the copper tube to the pressure transducer placed indoors.

Moisture: Wetting-drying cycles were measured using two resistance-type moisture sensors: small ceramic blocks and conductive pins. Ceramic sensors were constructed, consisted of two wires fastened with conductive epoxy to opposite sides of a 5 mm thick block cut from a clay brick (size approximately 19 mm x 10 mm x 5 mm). They were attached with epoxy to the surface of the lath or the brick wall. When the sensor absorbs moisture, its electrical resistance drops. Results are presented in terms of conductance and are referred to as wetness (wetness = 800 / R, where R is sensor output in MΩ). The scale is arbitrary; it is only intended to show wetting and drying cycles.

The pin sensors consist of two insulated commercial moisture pins (2.4 mm diameter, 53.4 mm long). The pins were driven 10 mm deep, 25 mm apart, into the wood. The electric

resistance between the 4 mm uninsulated tips of the two pins gives an indication of the moisture content. Moisture pins can determine the moisture content of wood to within 2% if corrected for wood species and temperature.

Data acquisition system: The sensors were connected to a data acquisition system. The system automatically sampled and stored the output from every sensor once a minute. In addition, the data were averaged and saved every 10 minutes and every hour. In-house software was written to provide the output data. No pre-screening of the data was done prior to averaging.

Measurement Results

Air leakage

The equivalent leakage area of the building was determined[2] to be 1.34 m^2 at 10 Pa (approximately 14 cm^2/m^2 normalized leakage area, i.e. 0.14% of envelope area). Indoor air temperature at the time of the test (Oct. 17, 1994) was 23°C. Outdoor air temperature was 16°C. Weather records showed the average hourly wind speed was 0 to 7 km/h. The building has a normalized leakage area at least twice that of pre-1945 houses surveyed in Saskatoon [see p 34 ref. 2].

A thermographic survey indicated that most of the leakage occurred at the top of the mansard roof (attic space and dormer); no other large leaks were observed. The thermographic survey of the building was conducted in the evening following the air leakage test; the building could only be pressurized to 6 Pa above the outdoor air pressure due to the leakiness of the building.

Air pressure

The indoor air pressures (hourly average) were below the outdoor air pressure at the locations monitored (for example, during Dec. 95, mean values were 7.7 Pa & 2.5 Pa for the first and second floors respectively, Fig. 4). The air pressure in the wall cavity was also higher than indoor air pressure (during Dec. 95, mean values of 2 Pa & 0.6 Pa for first & second floors respectively). The negative indoor air pressures essentially eliminated the leakage of the humid

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[2] Standard CAN/CGSB-149.10-M86, *Determination of the airtightness of building envelopes by the fan depressurization method.*

indoor air into the wall cavities and thus eliminated the potential for condensation on colder cavity surfaces. On the other hand, cold exterior air travelled through wall spaces, ceiling spaces and openings in the interior surfaces. This caused localized cold spots and ice formation on interior surfaces in several areas including walls and ceilings that have connection to the outdoors. This led to condensation and crack development. The latter was probably caused by dimensional changes due to changes in moisture content and temperature of the wall and ceiling materials.

The small diameter copper tubing was sometimes blocked by water during wet periods or by dew. This led to inconclusive high pressure readings between indoors and outdoors. False data was discarded. In future, a large diameter fitting should be attached to the end of the tube to stop capillary action and shed water.

Thermal performance

Indoor temperatures: During the summer, indoor air temperatures varied between 13°C and 22°C. Figure 5 shows that indoor air temperatures frequently dropped to 13°C during the night and rose to over 20°C the following morning. The figure also shows that indoor air temperatures tend to follow the diurnal variations in outdoor air temperature with a lag of about 12 h. This suggests that the HVAC system, which operated continuously, had limited control of indoor air temperatures especially during the summer. During the winter the variation was small (typically 20 to 23°C; Fig. 6) because the radiators had individual thermostats.

Wall-cavity: The variation in the surface temperatures of the brick and the lath within the wall cavities (air spaces in the walls) generally followed the daily average of the outdoor air temperature partly due to the damping effect of the thermal mass of the masonry wall (Figs. 5 & 6). The variations of surface temperatures in the east wall-cavity were less than those for the west wall-cavity surfaces. This is because the east wall is shaded by a neighbouring highrise building and a large tree. In addition, a west wall normally receives more sun than an east wall.

Attic space: Figure 7 shows the variation of temperature in the attic space above the third floor mechanical room during winter and summer. Solar heat caused a large increase in the roof sheathing and attic temperature in the summer. In winter the roof sheathing and air temperature were more stable and were usually much higher than the outdoor air temperature (15-20°C higher; the temperature only approached the exterior temperature on windy days).

This indicates a large heat loss into the attic space with the major part probably caused by air leakage. This also explains the ice-damming which is a problem on this building.

Moisture performance

Indoor air: The RH of the indoor air varied from room to room and also from month to month (Table 1). It far exceeded specified indoor conditions. The variation in RH during August was partially due to the large variation in indoor air temperatures. Figure 8 shows that variation in indoor air dew-point during August had a diurnal variation similar to the outdoor air dew-point (the dewpoint is representative of the moisture in the air). Measured RH during the summer shows that the HVAC system did not adequately control the relative humidity. Possible causes may include improper operation, location, or type of the humidistat; faulty controller operation; or insufficient dehumidification capacity of the HVAC system.

Table 1 Variation in Relative Humidity

	Dining Room		Foyer		Bedroom	
	Min	Max	Min	Max	Min	Max
August 95	42	76	39	73	38	80
November 95	34	50	27	51	28	43
January 96	21	50	19	49	22	44

Wall cavity: The RH in the wall-cavity exceeded 60%. Figure 8 shows little variation in the cavity air dew-point during the summer while in winter it followed the variation in outdoor air dew-point. The results also indicate that, during summer, the brick is drying into the cavity air which led to higher dew-point in the cavity than in the indoor air.

Attic space: The variation of the RH in the attic followed the diurnal variation of the outdoor air with a time lag in both winter and summer. It reached up to 89%. The dew-point of attic air was 0 to 8°C higher than outdoor air.

Windows: Extensive condensation and ice buildup was observed on the single-glazed window during the winter months. The surface temperature of the single-glazed window in the dining room dropped below the dew-point for several days during November and for most of January (Fig. 9) and apparently below freezing. Water stains and wood swelling were evident on the sill of the dining room window.

Wetting-drying cycles

Exterior surface: The data from ceramic moisture sensors mounted on the exterior surfaces showed periods of wetting during precipitation (Fig. 10). They dried out within 6 to 36 hours onset of precipitation.

Wall cavity and attic space: No condensation was detected within the air spaces of the walls at the locations monitored. The surface temperature of the brick and the lath within the wall-cavities was always higher than the dew-point of the cavity air. The ceramic and moisture pin sensors within the wall cavity indicated that no wetting occurred on the masonry interior surface nor the lath (Fig. 10).

The temperature of the wood sheathing of the attic roof was usually higher than the dew-point of the attic air. However, on one occasion, in January 1996, the ceramic moisture sensor indicated surface wetting of the roof sheathing because of condensation. The temperature of the roof sheathing in the attic dropped more than 12°C below the dew-point at about 6 a.m. The ceramic sensor dried out about 11 hours later. The moisture pins, inserted in the sheathing to a 10-mm depth, indicated that moisture from the condensation was insufficient to affect the sensor at that depth.

The RH sensor in the cavity of the north knee-wall indicated excessive humidity, about 100% RH, within the wall-cavity on January 30, 1996. Examination of the knee-wall cavity indicated ice damming on the roof had caused water to leak through a crack in the roof slate, through torn roofing paper and a cutaway in the roof sheathing. As a result, monitoring of this wall section was terminated part-way through the monitoring program pending repair of the roof defect. This indicates the usefulness of sensors in critical areas to detect hidden problems before serious damage can occur.

Conclusion

The first two floors of the house, under low wind conditions, were operating most of the time under a negative air pressure with respect to the outdoor air pressure. As a result, cold-air infiltration through wall partitions and ceiling spaces caused localized cold spots and ice forming on the interior of walls and ceiling.

The results also indicated that the brick walls are unlikely to experience internal condensation problems as long as the walls are subjected to a negative air pressure. However,

because the building is quite leaky, the negative pressure created other surface condensation problems. Negative pressures are not a solution unless the size of the leakage paths are reduced (between the roof, ceiling spaces and walls). Air leakage at roof and dormer levels must be addressed.

The windows require immediate attention. The high indoor humidity has caused excessive condensation on the windows. To reduce the adverse effect of condensation on the durability of the windows, the thermal performance and airtightness of the windows should be improved. Thermal performance could be improved by using double glazed storm windows. In this way the historic value of the windows would be least affected. The original storm windows can be kept in storage.

The relative humidity of the indoor air varied considerably from room to room and also from month to month. It reached up to 80%. This large variation in humidity is not desirable for the preservation of the historical artifacts. A complete review of the HVAC system is required. Factors to consider include the location of the RH control sensor, ensuring it controls the dew-point, and checking its calibration and operation. Also check the de-humidification capacity of the HVAC system. After the HVAC is modified and air leakage at roof and dormers is addressed, it will be necessary to monitor the building envelope again. The HVAC system should also be monitored.

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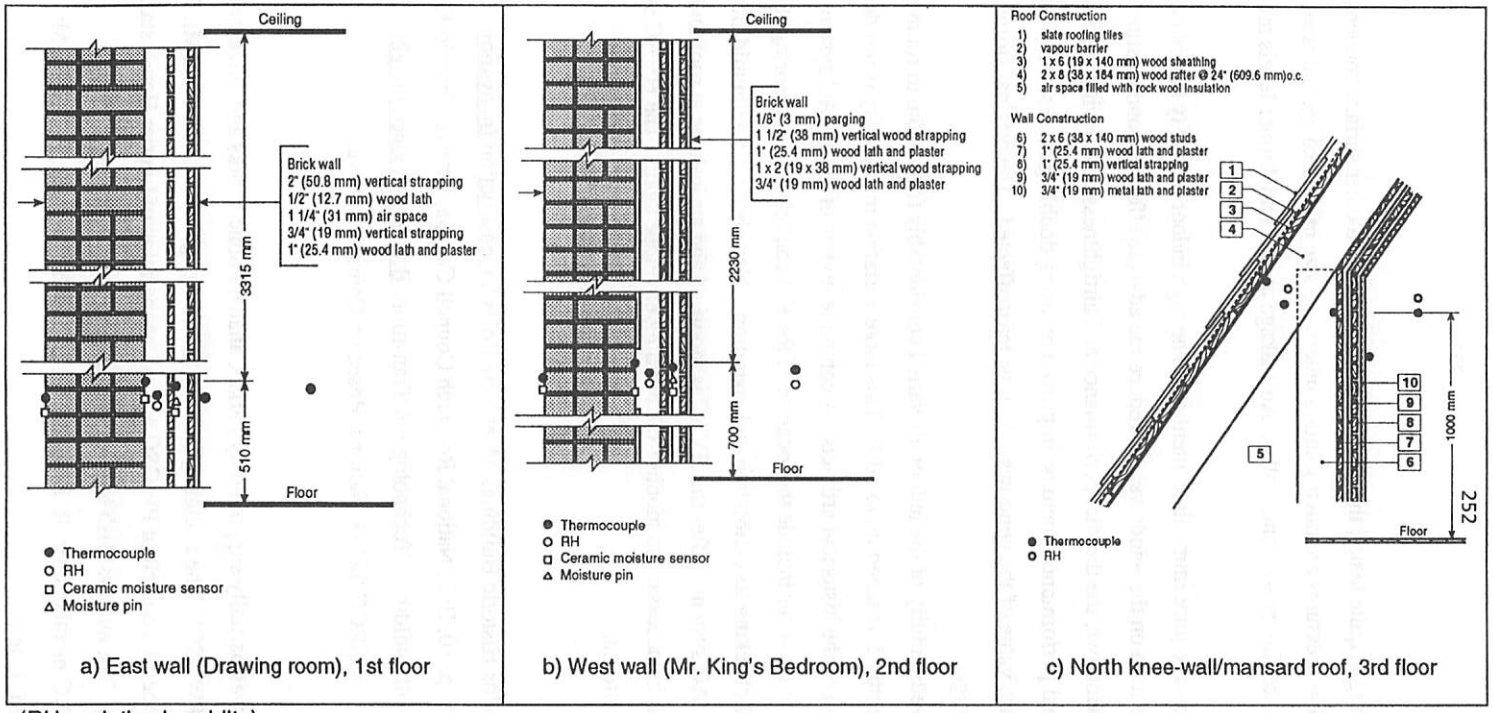
2. NRC, 1990. Small Buildings, Technology in Transition. Building Science Insight, Proceedings No 17, NRCC 32333, National Research Council, Ottawa.

Acknowledgment

This work was partially supported by Parks Canada, Public Works and Government Services Canada (PWGSC). The authors gratefully acknowledge the assistance of Mr. Ron Wilson and Mr. Robert Campbell of PWGSC and the cooperation of Laurier House staff during the site monitoring. The authors wish to acknowledge the contribution in the field measurements of IRC members Mr. R. Demers, Mr. L. McSheffrey, Mr. R. Belkie, Mr. R.J. Magee, and Mr. J.M. Ullett.



(RH : relative humidity)

Figure 2. Sections through monitored walls on 1st, 2nd and 3rd floors showing instrumentation

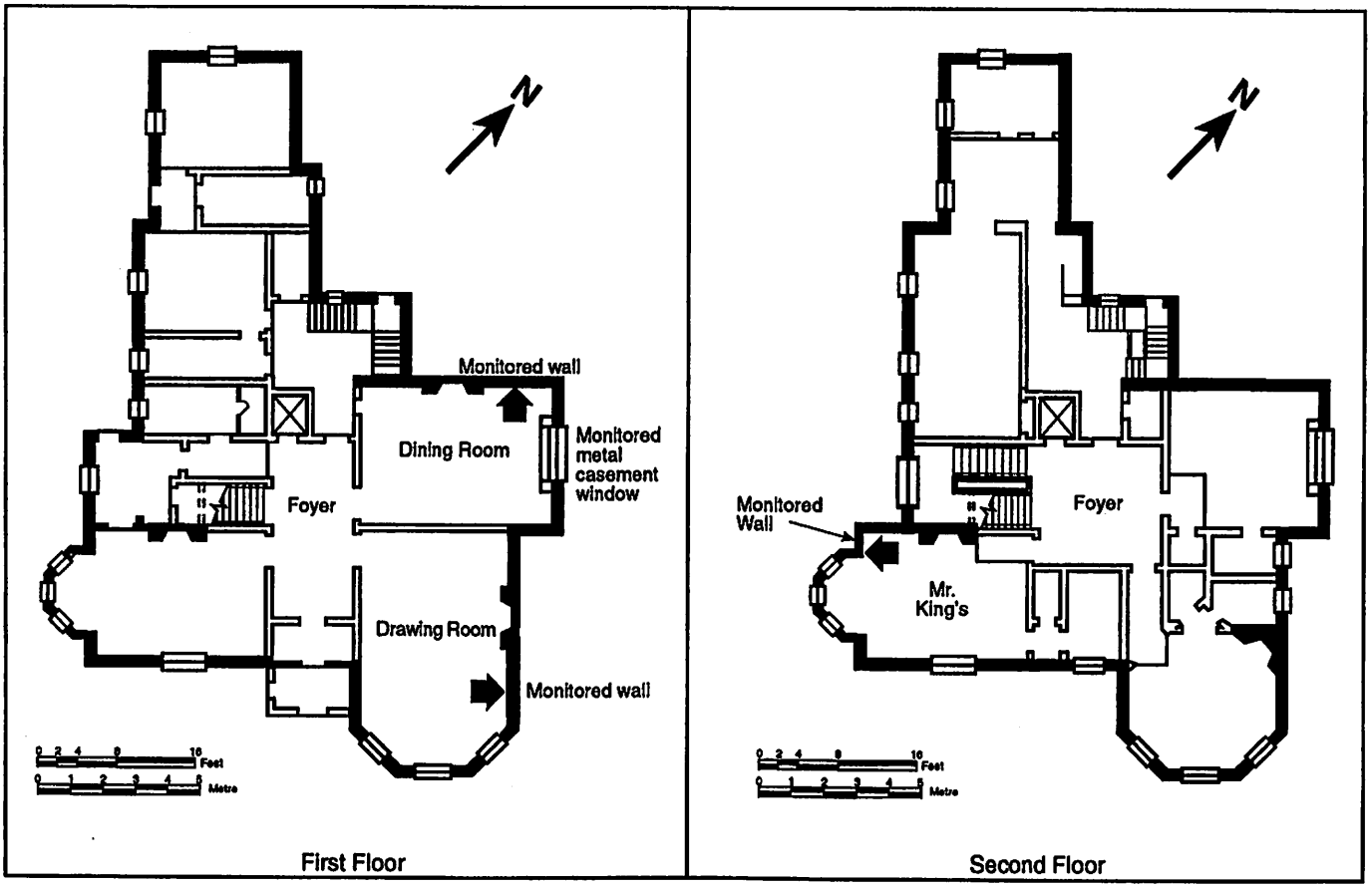
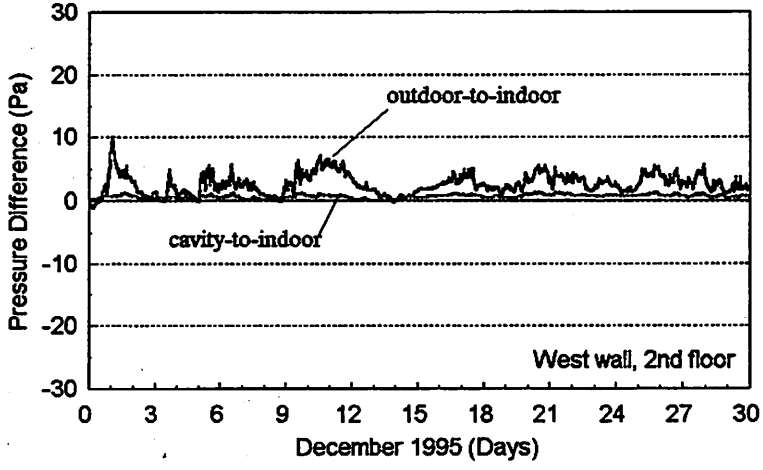
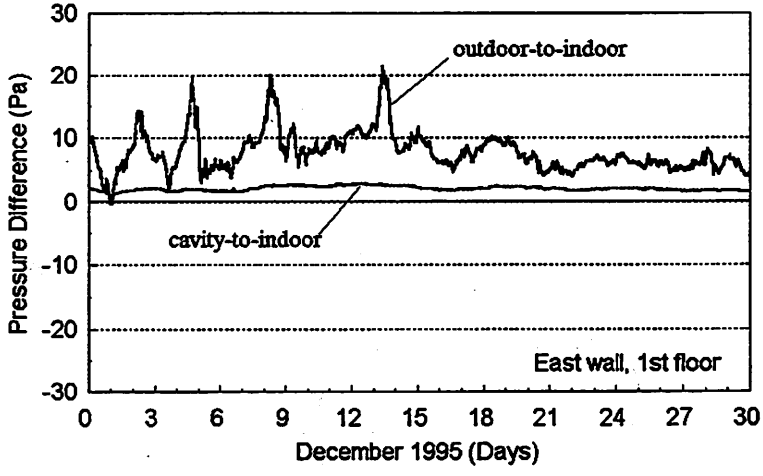


Figure 3. Plan of first and second floors of monitored house showing the location of monitoring sites

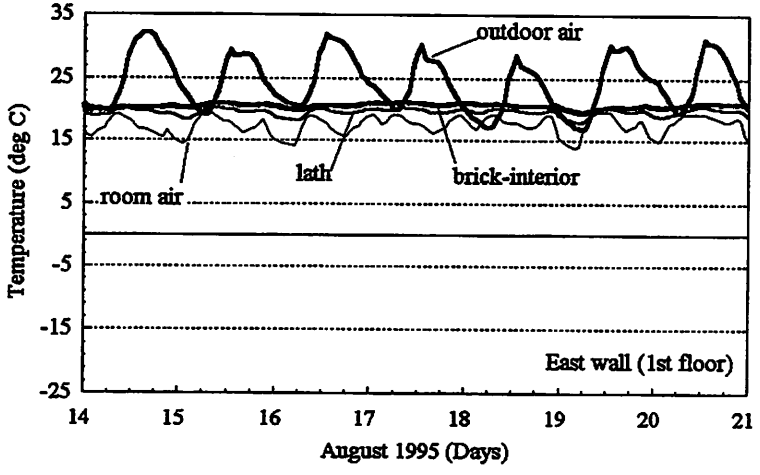


a) West wall, 2nd floor (Mr. King's Bedroom)

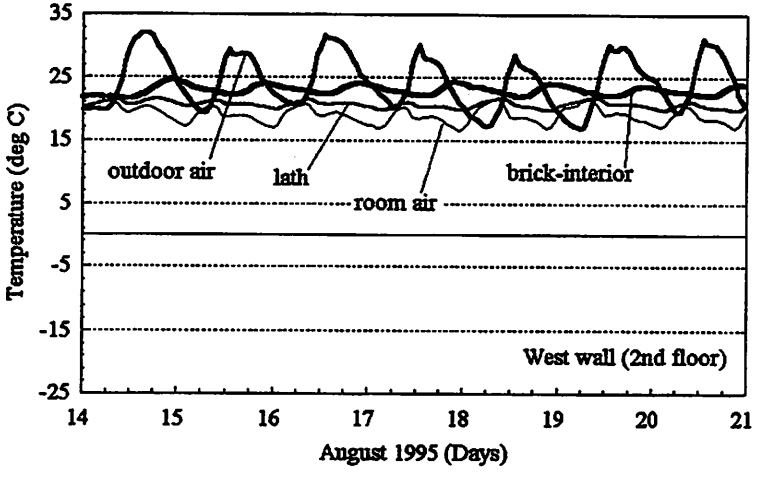


b) East wall, 1st floor (Drawing room)

Figure 4. Pressure differential, outdoor-to-indoor and wall cavity-to-indoor, December 1995.

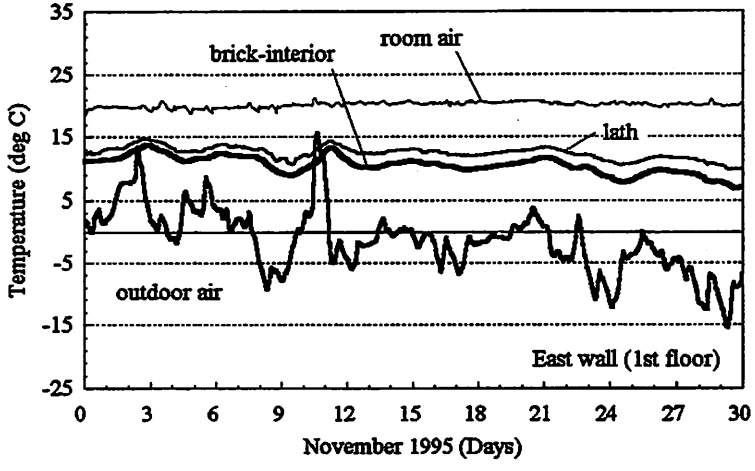


a) East wall, 1st floor (Drawing room)

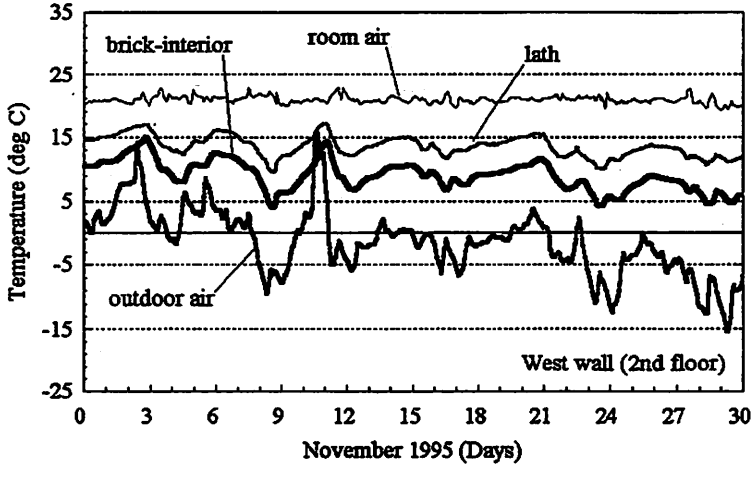


b) West wall, 2nd floor (Mr. King's Bedroom)

Figure 5. Temperatures of brick interior surface and intermediate lath within wall cavities and indoor and outdoor air, for selected periods in August 1995.

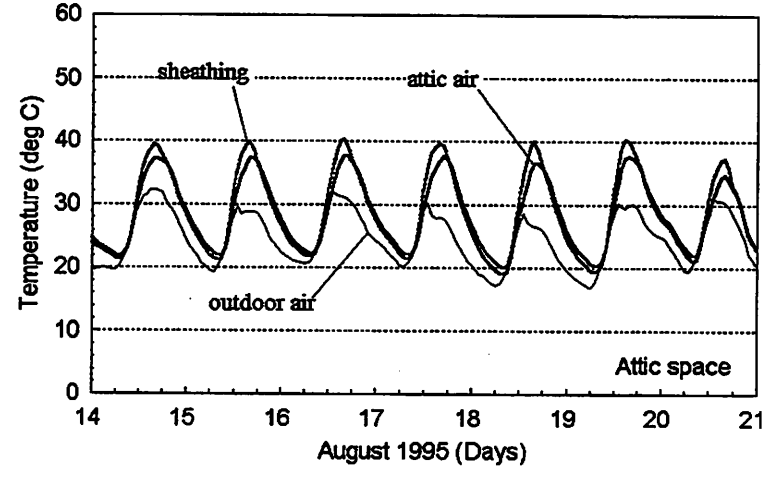


a) East wall, 1st floor (Drawing room)



b) West wall, 2nd floor (Mr. King's Bedroom)

Figure 6. Temperatures of brick interior surface and intermediate lath within wall cavities and indoor and outdoor air, November 1995.



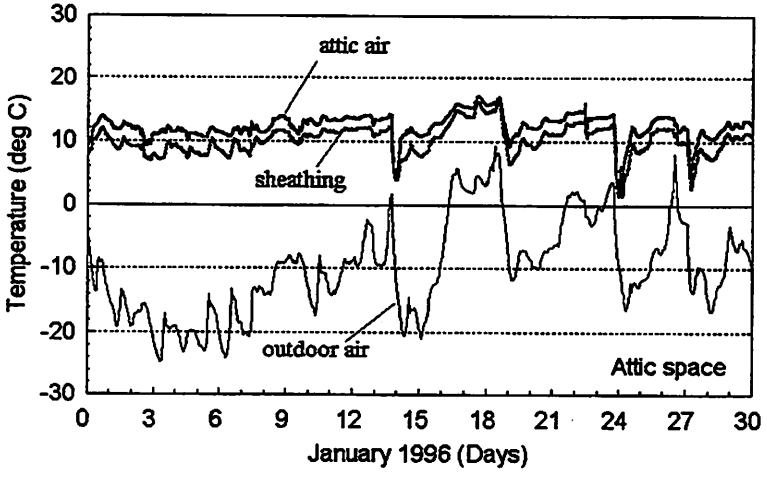
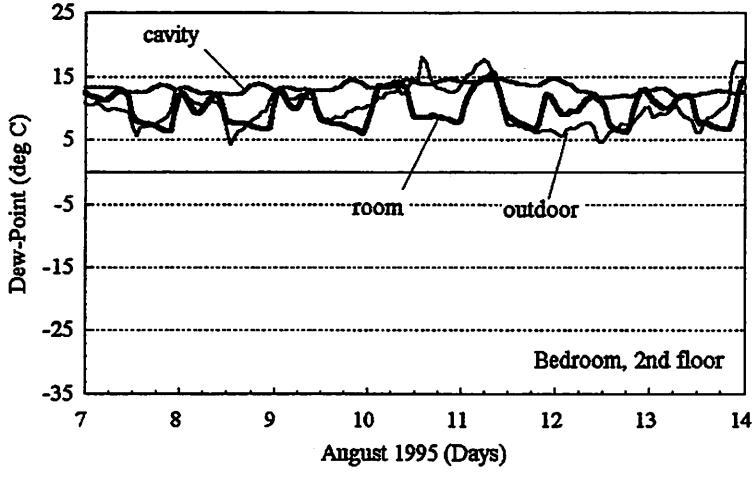


Figure 7. Temperatures of roof sheathing, attic air and outdoor air, for selected periods in August 1995 and in January 1996.



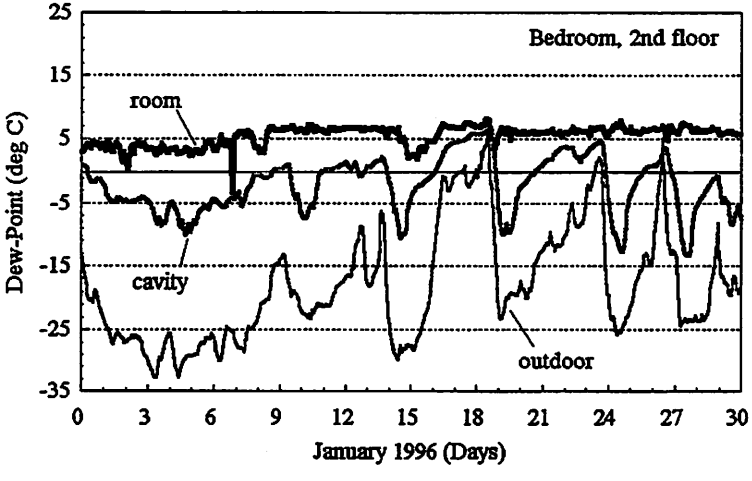
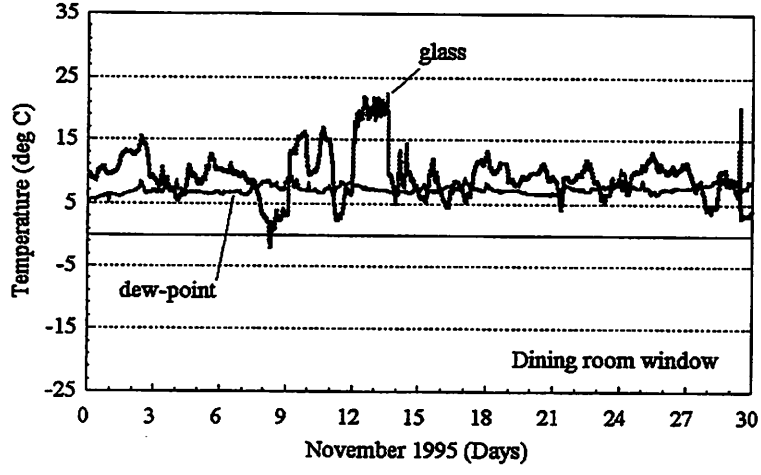


Figure 8. Dew-point of room air, wall cavity air and outdoor air, Mr. King's Bedroom (west wall; 2nd floor), for selected periods in August 1995 and in January 1996.



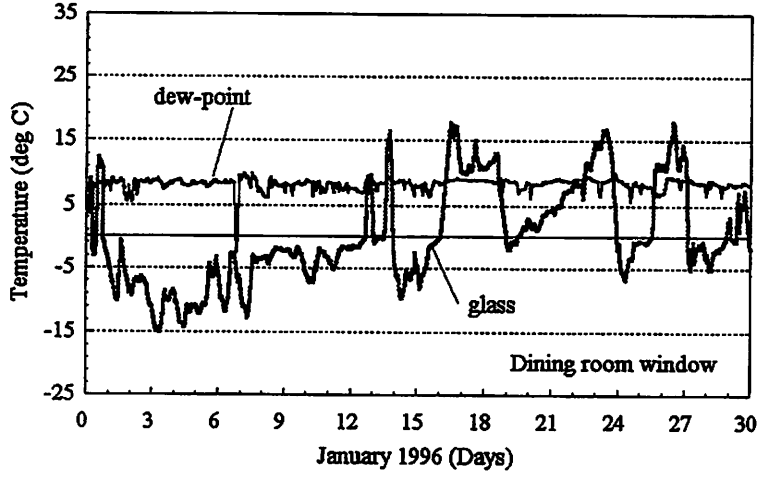
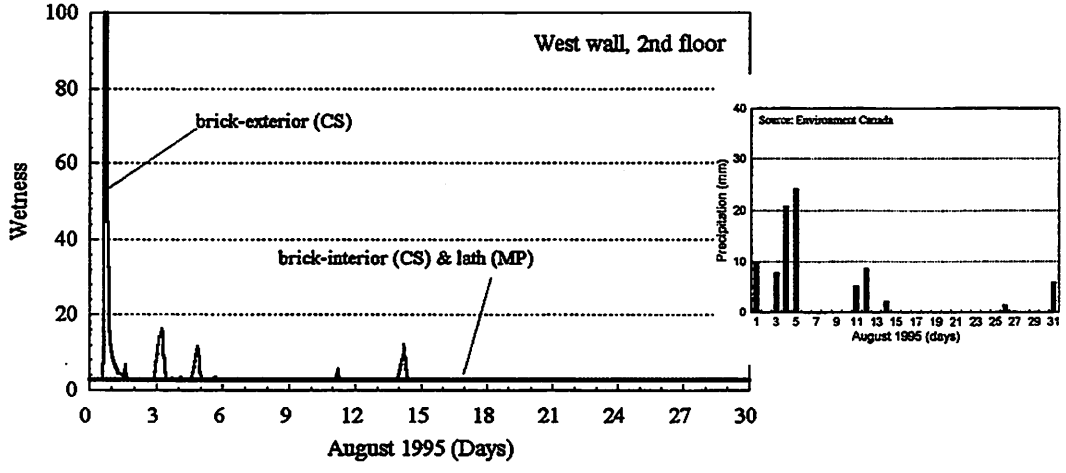


Figure 9. Temperatures of dining room window glass (single-glazed) and dew-point of indoor air, November 1995 and January 1996.



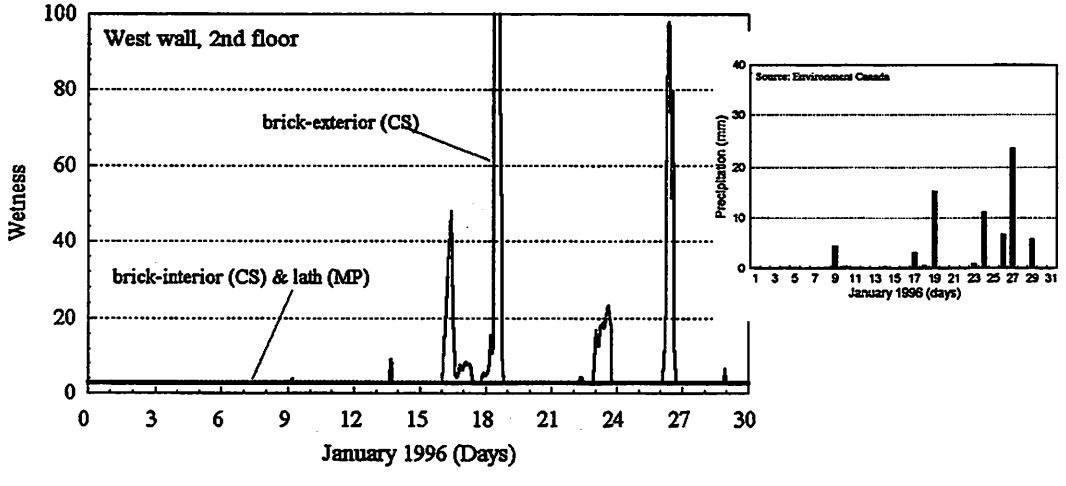


Figure 10. Wetting-drying cycles, west wall (Mr. King's Bedroom), 2nd floor, August 1995 and January 1996. [scale is arbitrary].

MASONRY/STEEL STRUCTURES
A PERFORMANCE REVIEW

David P. Cousins[1] and Mike Panahi[2]

ABSTRACT

Steel framed structures enclosed by non load bearing masonry walls were used in the Toronto area in the 1970's to construct large low-rise facilities such as shopping centres and industrial/ commercial buildings. As the function of the masonry was strictly to separate the interior space from the weather this type of construction was expected to be durable and achieve its 50 year design life with minor maintenance.

Performance of these structures to date indicates that the extent of structural problems are directly related to construction deficiencies with respect to:

- Inadequate wall Ties
- Discontinuous shelf angle supports
- Vertical misalignment of exterior masonry walls and structural steel frame and masonry supports
- Inclusion of cavities in solid masonry wall design
- Inadequate control joints

This paper presents the engineering investigative procedures necessary to identify and assess the inherent structural defects, assess their impact on structural safety and long term performance of the exterior masonry walls of this type of structure. The engineering analysis of an existing shopping mall in the Toronto area is used to demonstrate the limitations of these procedures and the impact on the design of a rehabilitation program with this type of construction.

While the structural steel frame is still very much in use today to construct large low-rise facilities, the exterior masonry walls have given way to precast concrete/prefab wall panel systems. The issues with performance of our existing steel framed masonry wall structures are still valid and must be addressed during design and construction of these types of facilities.

The design issues are; moisture movement through exterior walls, connection details to structural steel frame to provide adequate support and allow thermal movement, size and spacing of adequate thermal movement control joints in masonry wall structures, separation of wall sections of different stiffness, selection and use of ties and anchors of suitable corrosion resistance to achieve the design life of the structure.

The construction issue is the provision of adequate on site supervision to ensure that the wall construction follows the design and that changes necessitated by misalignment of components are properly addressed by the construction team.

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MASONRY STEEL STRUCTURES
A PERFORMANCE REVIEW

INTRODUCTION

Masonry exterior walls have been utilized to enclose structures in the Toronto area since the early 1900's. Steel framed structures with exterior walls of non-load bearing masonry were used extensively in the 1970's to construct large low-rise facilities including shopping centres and industrial/ commercial buildings. The non-load bearing masonry walls were typically constructed of 6 to 8 inch concrete block back-up with 3 inch face brick. The two wythes were connected by masonry bonding units or metal ties. In these structures it is apparent that the cavity widths as governed by the wall design were not properly incorporated during construction.

The following utilizes an analysis of a structural steel frame masonry wall structure which was built in the Toronto area in the late 1970's and evaluated by the authors in 1995/96 to outline the engineering approach in the evaluation and rehabilitation of this type of structure and highlight typical defects encountered with this type of construction.

ENGINEERING EVALUATION PROGRAM

The engineering approach to evaluating this structure involved

- Cursory visual inspection of the structure to identify potential areas of concern
- Review of the architectural and structural design drawings
- Review with owner long term plans for the structure

The cursory visual inspection revealed crack development in the masonry panels at the roof level of the two storey steel structure, outward movement of masonry panels at the roof parapet and unusual staining patterns on the brick face.

An initial review of the architectural and structural design drawings indicated that the architectural drawings provided the concept for the exterior walls, the structural steel drawings indicated the structural steel frame and the steel supports fro the exterior masonry. However the vertical alignment of the structural frame and the exterior masonry walls and the resultant cavity widths was not addressed. Typical architectural and structural steel framing details are show in figures 1,3,& 5.

A review with the facilities management concluded that the present owners intend to continue operating the facility for the foreseeable future - the next ten year period, and preferred that the existing masonry exterior walls be maintained to preserve the look of the facility as opposed to retrofitting a new wall system. The concerns as established with the facility managers were:

- Public safety
- Repair priorities and costs
- Aesthetics

The Facility Managers and Owners input at this early stage is important in determining the level of engineering investigation required into the condition and details related to the exterior brick.

Considering the above, the engineering evaluation program was designed on the basis of the existing exterior brick walls being maintained for at least the next ten years.

The engineering evaluation program included:

- Visual mapping to correlate visually observable defects with the architectural and structural design details.
- Test openings at selected locations to determine as built details and assess the structural integrity of the steel shelf angles , their connections and anchorages and assess the structural integrity of the different wall tie systems used.
- Thermal scans of the exterior walls to assess air leakage and formation of ice in the masonry walls especially at the base of the parapet walls at the roof level.
- The installation and use of temperature and humidity data loggers in the masonry walls to monitor the environmental conditions within the cavities formed in the exterior wall construction of the two storey and single storey structure during the winter months.
- A laboratory test program to evaluate the discolouration of the calcite brick (concrete brick units) forming the exterior walls of this structure.

Visual mapping is an important engineering tool used to correlate visually observable defects with the structural steel frame and connections. In steel/masonry structures the visual inspection should address;

- Location and extent of cracking including measurement of crack widths at building corners, above openings, at vertical control joints at overhangs at perimeter floor and roof beam locations.
- Location and extent of bulging masonry at bases of walls and above and below shelf angles
- Locations of spalled masonry at roof parapet and below shelf angles
- Locations of outward movement of masonry at the top of walls and shelf angles at perimeter floor and roof beams
- Locations, spacing and width of horizontal soft joints and vertical control joints.
- Locations of discoloured masonry.

It is important to recognize that movement and/or bulging of masonry panels is sometimes not detectable during a visual inspection carried out at ground level. A visual inspection from the ground level is reasonably limited to a maximum of 4 stories. While major defects can be observed at greater heights, supplemental access to the wall areas is required to perform a proper visual inspection. This supplemental access can take the form of a swing stage, boatswains chair, or elevated platforms.

On the basis of correlation of observed defects with the structural and architectural design details, a destructive test opening program can be developed. Recognizing the limitations of a destructive test program, primarily cost, test opening locations are selected to address typical conditions and confirm as-built conditions for later comparison with the design details. The test opening program for this shopping mall facility was designed to address:

- Outward movement of the masonry at the roof parapet
- Crack development at the building corners
- Crack development at the overhangs
- Typical wall construction at the roof parapet, roof and second floor perimeter beams, overhangs and condition of components.
- Staining of the exterior brick at the roof parapet and at soldier course detail strips

The test openings at this structure revealed that the structural steel framing and details of the masonry supports ie. shelf angles and their connection to the steel frame were in general conformance with the design drawings. With respect to the masonry wall construction the openings revealed the following:

Roof Parapet - (refer to figure 1)

2 to 3 inches of outward movement of the brick at the shelf angle

Cavity width of 1.5 inches at parapet, Galvanized dovetail anchors 1 inch wide, 1/16 inch thick

Perforated flashing at shelf angle, No soft joint below shelf angle

Perimeter beam at roof and second floor - (refer to figure 3)
Cavity width, 3 inches, Galvanized rectangular 3/16 inch wire ties with drip
Discolouration of joints in fibrous insulation

Building Corner
Shelf angle discontinuous at column, Significant openings in block backup where it abuts column
No vertical control joint in exterior brick wythe
Discolouration of joints in fibrous insulation

Roof Overhangs
Shelf angle discontinuous at structural steel column, Downward rotation and excessive deflection of the shelf angle
No vertical control joint in exterior brick wythe at building corner, Discolouration of joints in fibrous insulation

Discoloured masonry - (refer to figures 5 and 6)
Dark stains close to the top of the roof parapet appeared related to joints in the sheetmetal cap and joints in the precast coping stones cap flashing, Stained brick further down in the wall, no link to any particular detail in the wall assembly
Stained brick at the soldier course detail strip linked to cavity included in wall construction.

Thermal scans of a building or facility are an extremely useful tool in locating defects or anomalies in the exterior walls. Thermal scans can cover large wall areas in a short period of time and allow on site real time comparisons of the thermal performance of different wall areas. Considerable care must be observed when carrying out a thermal scan and the interpretation of the images. Surface temperatures indicated in thermographs should not be interpreted as absolute but used for comparing to other wall areas at the same time. The infrared images are affected by several factors which are described in detail in CBD No.229[1].

The thermal scan of this structure was carried out in February 1996 and revealed significant air leakage into the roof parapet cavity emanating from the roof perimeter beams. A typical thermograph depicting this condition is attached as figure 8. The thermal scan also revealed formation of ice within the wall cavity at the base of the roof parapet at a few locations. At the soldier course detail strip the thermal scan revealed air leakage into the cavity above the strip as indicated in figure 6.

Monitoring of the environmental conditions in the cavity between the exterior brick wythe and the concrete block backup during the winter months provides useful information regarding the thermal performance of the wall assembly and the extent of moist warm interior air infiltration into the cavity space. Information obtained from the data loggers includes the date, time, temperature and relative humidity. The information downloaded from the data logger also indicates the number of counts the data logger has made within the specified time interval to establish the reading. This information is extremely useful in confirming erroneous results due to data logger errors.

Monitoring of the environmental condition within the cavity walls of this structure was carried out from December 1995 to April 1996. The locations monitored included:

- Roof parapets at the two story and single storey structures
- Mid wall height of the single storey structure at the soldier course detail strip
- Inside and outside air

The results of the monitoring are attached as table 1 and graphically displayed for the south parapet wall in figures 9 and 10.The monitoring confirmed significant air leakage as indicated by the thermal scan. Of the 22 data loggers installed 4 humidity data loggers failed likely due to damage during installation.

Laboratory testing can be utilized to confirm material properties and investigate anomalies as they relate to material performance. To further evaluate the cause of the stained brick at this site, brick samples were obtained from those areas exhibiting no staining, slight staining and dark stained areas. The bricks were comparatively tested in accordance with CSA A165.2-94 [3]

The compressive strength results indicated that the brick quality is extremely variable with individual strengths varying from 33.2Mpa to 70 Mpa.

The saturation coefficient is calculated from the 24 hour cold water absorption and the 5 hour boiling water absorption. It is a measure of the bricks ability to uptake water which is affected by the pore structure including void spacing and diameter of the voids and is an indicator of the freeze thaw durability of the brick [4]. The saturation coefficient for this brick varied from 0.61 to 0.73 and is within the CSA limits.

Initial rate of absorption tests were carried out to evaluate the surface absorption characteristics of the brick. The average of 27 grams uptake was below an industry suggested maximum of 30 grams however individual results varied from 6.3 to 52.5 grams indicating extreme variability in the surface absorption characteristics which is likely contributing to the random staining or darkening of the brick face due to natural pollutants and surface water runoff.

Petrographic examination is a useful tool to detect deleterious aggregate and cement paste/aggregate reactions which can contribute to the deterioration of the brick. A petrographic examination of the calcite brick samples obtained from this site was carried out, however it did not reveal any problems with the cement paste that would contribute to the staining. Microscopical examination revealed that the stained brick had lost 1/64"(0.5mm), of the cement paste from the exposed surface of the brick. As a result the colour from the cement paste had been lost and the grey colour of the exposed aggregates had changed the appearance of the brick units. The loss of cement paste from the exposed face of the brick units is attributable to freeze thaw cycling of the brick face in a water saturated condition.

REHABILITATION DESIGN

A rehabilitation program designed for an existing masonry/steel structure must first address the structural safety concerns with the exterior masonry walls and then consider and incorporate where practical details to improve the walls performance including reduction of air leakage and water penetration considering the Owner's long term requirements.

The rehabilitation program for this structure addressed:

- Removal and replacement of the masonry panels where significant outward movement was observed and extension of shelf angles to provide continuous support at the building corners
- Securement of the bolted connection at the shelf angle supports by welding
- Installation of flashing and air barriers at roof perimeter beams
- Installation of vertical control joints at building corners
- Installation of vertical control joints at building overhangs
- Venting of the wall cavities at top and bottom
- Installation of new sheetmetal coping at roof parapet

During the rehabilitation design process the feasibility of sealing significant air leakage paths in the exterior walls was investigated. The thermal scan and wall monitors indicated that the majority of moist air leakage was occurring around the roof perimeter beams. While these air leakage paths could be sealed from the exterior where the masonry was removed to affect structural repairs at other locations, the feasibility and effectiveness of sealing from the interior had to be determined especially considering that the inside face of steel beams and decking was fireproofed. A trial sealing program was carried out where the joints above and below the roof perimeter beams were sealed from the interior and the result evaluated by thermal scan. The trial was successful, resulting in air sealing of the

entire perimeter of the roof of the two storey structure. The construction at the single story structure was investigated however due to interior construction, sealing of the air leakage paths from the interior would prove too disruptive to the operation of the facility and not feasible from a cost standpoint. As the exterior masonry was in good condition, with the exception of the stained brick at the soldier course detail, the rehabilitation design called for the venting of the cavity at the top and bottom of the cavity and installation of through wall flashing at the bottom of the cavity to direct the condensation that will occur to the exterior without saturating the brick face. Typical rehabilitation details are shown in figures 2, 4 and 7.

RESTORATION

During the restoration hidden structural problems which were not identified in the investigation of the exterior masonry walls of the two storey structure were uncovered during the removal of the masonry panels. The significant observations made during the restoration are summarized as follows:

Roof Parapet

- Corrosion of the flange of the shelf angle varying from 1/64 to 1/16" (This represents less than a 20% section loss).
- The anchor bolts connecting the shelf angle`brackets to the top flange of the steel beams were loose at several locations.
- Galvanized Dovetail ties - 1 inch wide and 1/16 inch, were installed 16" o/c vertical -32" o/c horizontal, first tie at 16" above shelf angle.
- Corrosion of the first row of ties above the shelf angle was noted on the underside of the dovetail anchor extending from the portion embedded in the brick mortar joint out into the cavity. No measurable section loss, other ties found to be in good condition.
- At the first row of dovetail anchors above the shelf angle the dovetail slot did not provide any lateral restraint for some of the anchors.
- The cavity width varied from 0.5 to 1.5 inches

Roof Perimeter Beams

- Galvanized corrugated strip ties - 1/64" were sometimes used instead of rectangular wire ties to anchor the brick to the concrete block backup. Embedment in the brick was a maximum of 1 inch. Corrosion of strip ties evident on the underside of the strip tie extending from the portion embedded in the brick mortar joint extending out into the cavity. No measurable section loss.
- Galvanized rectangular 3/16" wire ties with drip were installed in general at spacing 16" o/c vertical - 32" o/c horizontal, first tie below the steel beam varying in distance from 24" to 56" below the shelf angle. No ties were noted within the web of the beams.
- Galvanized wire ties were found to be in good condition with no evidence of corrosion
- The cavity width varied from 4 to 5 inches.

Building Corner

- Shelf angle discontinuous at structural steel column. Unsupported length up to 36 inches from column face noted.

Roof Overhangs and 2nd Floor Perimeter Beams

- Vertical misalignment of shelf angle with brick wythe resulting in 0.5 to 1 inch of brick bearing on shelf angle support.

Ramp Parapet

- Brick facing appeared to be constructed before concrete parapet and used as a braced form.
- Galvanized wire ties found embedded in concrete parapet installed in general at spacing 16" o/c vertical -32" o/c horizontal. Corrosion of the wire ties was evident. No measurable section loss was noted.
- The cavity width varied from 0 to 0.5 inches.

The above findings indicated that the wall construction did not comply with the National Building Code of Canada

1975 [5] with respect to tie type, spacing and cavity width which was in enforce at the time of construction and did not comply with the original architectural design drawings with respect to tie spacing and cavity width.

Sections 4.4.5.10 thru 4.4.5.16 of the NBC 1975 indicate the following:

- Metal ties to extend to within 1 inch of the inner and outer faces of the wall face of the wall
- Spacing minium of 18"o/c vertically and 36"o/c horizontally
- Metal ties to be corrosion resistant 3/16" diameter rods
- Cavity to be not less than 2" and not more than 3 inches

A review of the current Ontario Building Code requirements which references CSA CAN3 -S304-94, Masonry Design for Buildings [6], CSA CAN3 A371-M, Masonry Construction for Buildings [7], and CSA CAN3 -A370-M, Connecters for Masonry [8], indicates that the masonry as built does not meet requirements with respect to spacing, tie type, lateral restraint of dovetail anchors and shelf angle support of masonry.

For dovetail anchors the maximum free play allowed under the current standard is 1.2 mm. This was exceeded at the anchor immediately above the shelf angle. With respect to the spacing of the anchors this in general met the requirement of 400 mm o/c vertical and 800 mm o/c horizontal for a maximum cavity width of 40 mm. While the situation of inadequate lateral restraint was rectified where the masonry panels were removed and replaced, the lateral restraint provided by the existing dovetail anchors immediately above the shelf angle at the remaining panels was questionable. To address the possibility of outward movement above the shelf angle installation of stainless steel spiral retro ties was considered.

Spiral retro ties are installed from the exterior of the brick wythe through a pilot hole and tie the brick wythe to the back up wall. To establish maximum tie spacing and minimum embedment, on site testing is required as detailed in section 12 of CSA CAN A370. Spiral and adjustable retro ties require on site testing to establish spacing and fastener embedment required to meet design loads which is described in detail in reference [9]. Separate tests are required to establish pullout loads in the backup at different embedments and in the brick facing through the mortar joint and through the brick. Testing at this site revealed that while embedments of up to 2.25" in the concrete were achievable and resulted in the highest pullout load of 1243 lbs, the anchors could only be reliably installed to 1.5" depth. Utilizing working stress design and a factor of safety of 4, the tests indicated that a spiral tie spacing of 16" o/c vertical and 24" o/c horizontal would meet the criteria. However, the testing revealed extreme variability in pullout strengths from 761 to 1470 lb force in brick and 307 to 1243 lb force in the concrete parapet. Considering the variability of the pullout loads the spacing of the connectors was reduced to 8" o/c vertical and 24" o/c horizontal and thereby reducing the attributable wall area to ½ of the conventional spacing.

For the conventional rectangular wire ties the spacing of the anchors in general met the requirement of 400 mm o/c vertical and 800 mm o/c horizontal based on a maximum cavity width of 150 mm. However the wire ties contained drips which are not covered by CSA A370 and by nature reduce the buckling strength of the tie. This type of tie was utilized in the 1970's on the premise that the formed drip would cause water entering the cavity to drip down the cavity rather than crossover to the other wythe. The National Concrete Masonry Association has carried out comparative testing of cavity wall ties as reported in their TEK data sheets 99 [10] and 138 [11]. Compressive buckling strengths reported in TEK 99 for rectangular ties based on a cavity width of 4.5 inches are as follows:

- 3/16 straight wire tie - 577 lb force average failure load
- 3/16 crimped wire tie - 420 lb force average failure load

Full scale wall tests to evaluate the load carrying capacity of cavity wall tie systems as reported in TEK 138 indicate that for rectangular ties spanning a cavity width of 12 inches at a spacing of 16" vertical and 32" horizontal, the average maximum load was 93.6 PSF. Based on a contributing wall area of 3.58 sq.ft., the above yields a maximum tie load of 335.8 lb force at a 12 inch cavity.

Considering a maximum design tie load of 350 lb with a factor of safety of 4 and the above test data, the existing

rectangular wall ties at this site were considered to be structurally adequate at this time.

For the conventional corrugated strip ties the maximum allowable cavity width is 25 mm as per CAN A370. Sporadic installation of these ties had been observed at the roof perimeter beams. At the locations where the masonry was not removed at this site a monitoring program was set up to monitor the masonry walls for signs of distress.

CAN A370 requires that the projection of the brick wythe beyond the edge of the shelf angle support shall not exceed 30 mm or 1/3 of the wythe, whichever is less. Where the bearing is less than this requirement the shelf angle has to be modified to provide the required support considering the increased eccentricity of the vertical load from the brick wythe to the shelf angle support. This was dealt with by installing gusset plates supporting the shelf angle extension plate from the web of the steel perimeter beams as shown in figure 4.

MASONRY

During the start up of the restoration project in the spring of 1996 it was recognized that significant brick quantities would be required on site to replace the stained bricks and to replace the panels due to significant costs associated with reclaiming the existing brick. The original manufacturer of the brick was contacted regarding replacement bricks. Some of the significant problems which had to be overcome in obtaining replacement bricks were as follows:

- The colouring agents used to produce the colour of the brick at this site came from England and were no longer available.
- Readily available calcite brick did not match in size, colour and texture.
- The quantity of brick did not warrant shutting down a brick plant and retooling to produce the replacement brick of colour and size to match the existing.

Negotiations with the brick supplier resulted in an agreement whereby the bricks could be made at their block facility utilizing the original brick molds for this structure. The first trial replacement bricks were manufactured in June 1996 and visually appeared to match samples of the original brick. When installed in the wall on site they were noticeably off colour. Subsequently three trial batches were run at the owner's expense in an attempt to match the colour. Sliced and polished samples of the new bricks were visually compared with the original brick for similar matrix and colour of paste and aggregate to address the concern that when the new brick weathers it would still have a reasonable match with the existing brick. The finish of the replacement brick was not identical to original but was slightly more open and coarse as a result of the replacement brick be manufactured at a block facility where a tight compact appearance can not be achieved. From normal viewing distances this difference was not discernable to the untrained eye.

Shortly after the replacement bricks were installed it was apparent that the new brick retained moisture in the brick face for a longer period than the original brick. The quality of the replacement brick was verified in accordance with CSA Standard CAN A165.2 -94 and found to meet the requirements for an I 25 brick.

Trial panels of the masonry were selected to evaluate the feasibility of cleaning the masonry surface and effecting a more uniform blend between the existing masonry and the replacement brick. Various cleaners were tried as recommended in NCMA TEK 45 and reference [12] to remove the dark stains from the masonry with no effect. High pressure water blasting with and without detergents was attempted with little effect. Commercial light sandblasting was effective at removing most of the stained areas while improving the blend between the new replacement brick and the existing. At severely stained areas the stains reappeared anywhere from 24 hours to several days later following sandblasting. At these locations the stained brick were replaced. Recognizing that the surface absorption characteristics of the new and original brick would be changed by this procedure a sealer evaluation program was carried out.

A water based silane/polysiloxane sealer was selected for the evaluation on the basis of significant number of

successful applications within the Toronto area. The primary concern with application of a sealer on the exterior face of masonry is how it affects water vapour movement through the exterior brick which directly affects the freeze thaw durability of the brick. Freeze thaw durability of bricks can be evaluated by ASTM C76-91 as referenced in CSA A165.2 - 94, however, the test takes approximately 75 days to complete and the procedure involves freeze thaw cycling of the brick with the exposed surface completely submerged in water to a depth of 1 inch. Complete saturation for the duration of the test is an extreme condition and does not duplicate site conditions.

Considering the above, water vapour transmission and surface absorption characteristics of the new and old brick were comparatively evaluated to determine the effects of the sealer in both brick and block formulations. The results of these tests are presented in figures 11, 12 and 13 and indicate the following:

Absorption at 24 hours compared to unsealed brick control

New brick, brick sealer	-	18% reduction
New brick, block sealer	-	32% reduction
Old brick, brick sealer	-	25% reduction
Old brick, block sealer	-	79% reduction

Application of the sealer to the new brick showed dramatic reduction in the rate of surface water absorption during the first 24 hour period when compared to the unsealed control.

With respect to water vapour transmission the results indicated that the brick and block sealer drastically reduced the vapour transmission rate of the new brick when compared to its control but achieved a vapour transmission rate approximately equal to that of the old brick control and that of the old brick treated with the brick sealer.

With respect to the old brick, the brick sealer reduced the vapour transmission rate by approximately 9 % and the block sealer 73% when compared to the control.

Considering that the original brick in an unsealed state had proven freeze thaw durable for nearly 20 years, the brick sealer was selected on the basis of minium reduction in vapour transmission rate to significantly reduce the chance of adversely affecting the freeze thaw durability of the brick at this site.

Following the application of the brick sealer, samples were obtained from the sealed wall for comparison testing to determine if the full scale sealer application duplicated the results of the laboratory test program. Comparative water absorption results are plotted in figure 13 and indicate that for the new brick, the sealer application on site exceeded the reduction in water absorption as determined by the lab test program and for the original brick the reduction was essentially the same as that achieved in the lab test program.

CONCLUDING REMARKS

Performance of steel framed masonry low-rise structures is directly related to quality of original construction and specifically related to:

- Alignment of the steel frame, masonry walls and shelf angles
- Tie selection and installation including spacing and distance from vertical supports
- Cavity environment and level of corrosion protection provided to masonry ties
- Continuity of shelf angle supports
- Positive attachment of shelf angles to supports
- Location of vertical control joints especially at building corners and overhangs
- Extent of venting of the cavities between the inner and outer wythes of masonry
- Durability of through wall flashing and level of corrosion protection provided to shelf angles
- Level of protection provided by the sheet-metal/ stone copping against water penetration into the cavity and brick face at top of masonry walls i.e. roof parapets.

In evaluating and rehabilitating an existing steel framed masonry structure, the limitations of an engineering investigation must be realized. Hidden structural defects and/or deficiencies do not always result in structural distress which would be visible from the exterior.

During a rehabilitation program ongoing engineering input is required to ensure the structural adequacy of the wall assembly including evaluation of existing wall tie systems and shelf angle supports and on site testing and evaluation of retrofit tie systems.

With respect to the aesthetic appearance of the masonry as rehabilitated cleaning methods should be site evaluated and if sealer applications are to be utilized the water absorption and vapour transmission rates evaluated for the brick on site to maintain the freeze thaw durability of the masonry walls.

ACKNOWLEDGMENTS

The authors wish to acknowledge with thanks the on going effort of Ron Moore, Wycliffe Property Management in his support of proper engineering evaluation of existing structures and implementation of engineered rehabilitation programs to address structural safety and extend the service life of these structures.

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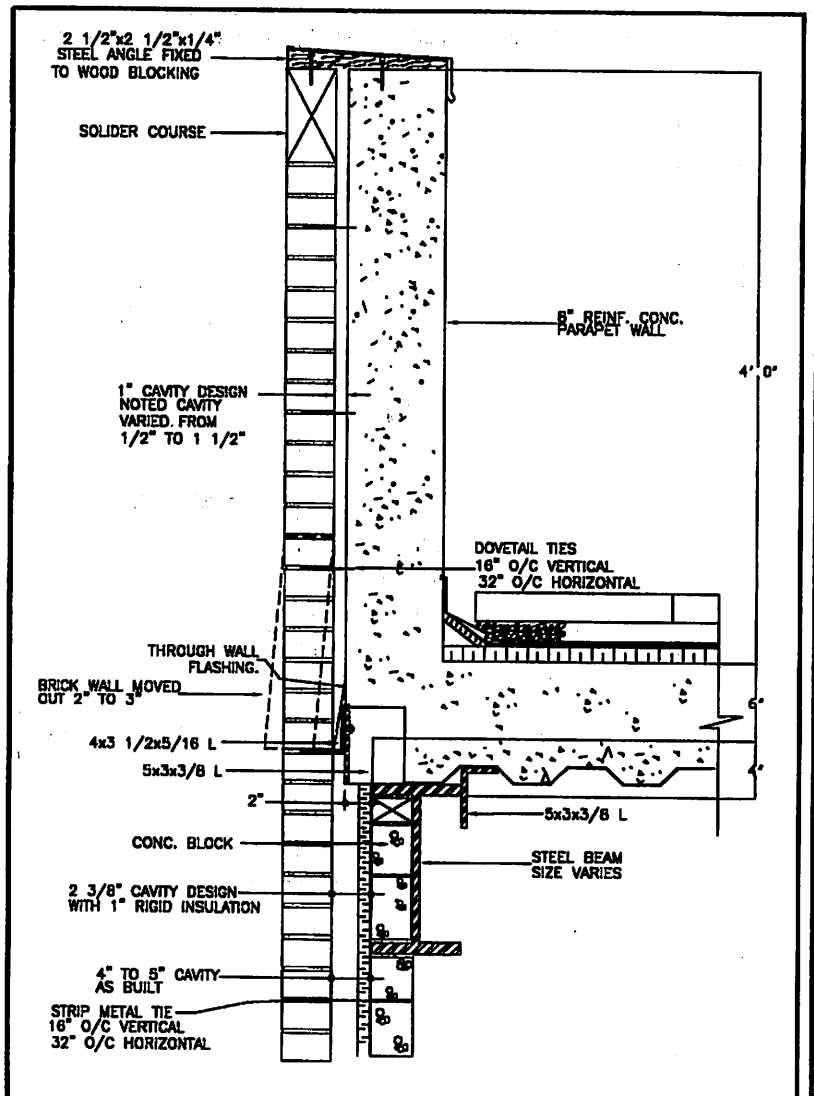


FIGURE 1. ROOF PERIMETER DETAIL– ORIGINAL DESIGN AND AS BUILT

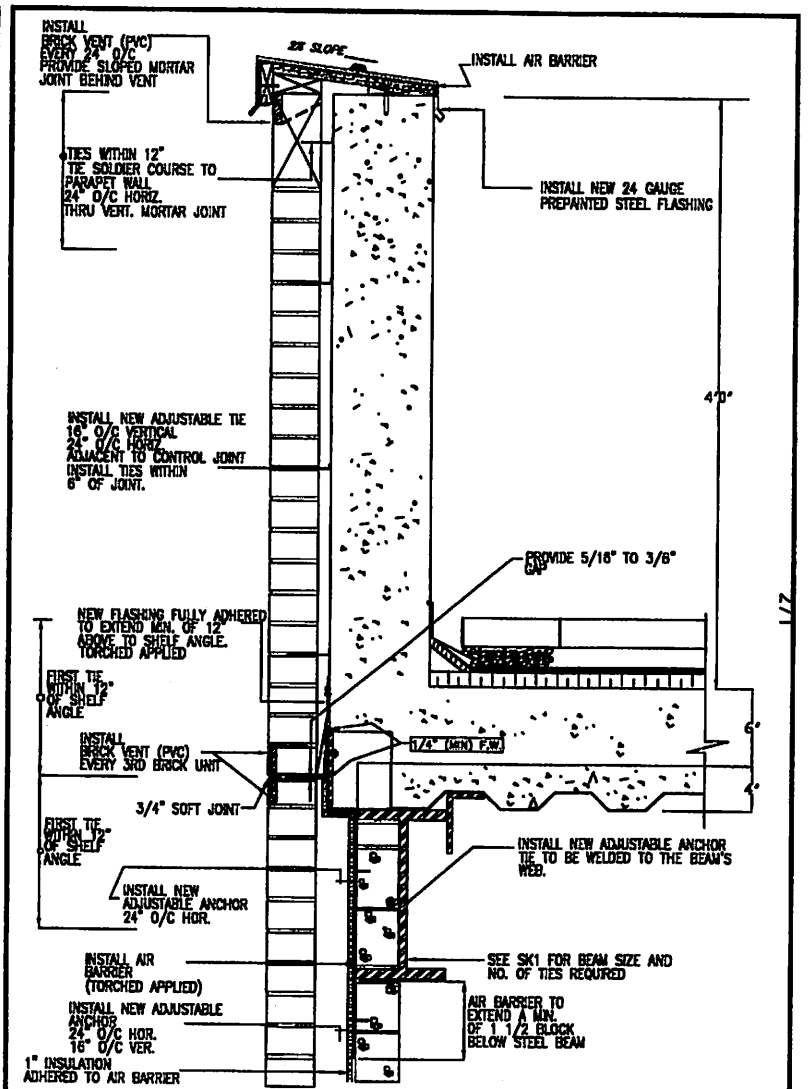


FIGURE 2. ROOF PERIMETER DETAIL – AS REPAIRED

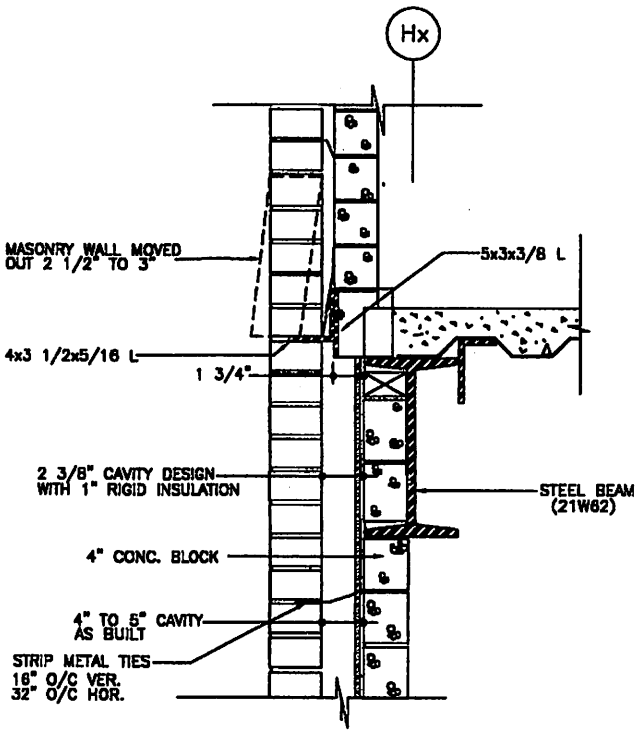


FIGURE 3. SECOND FLOOR SECTION – ORIGINAL DESIGN AND AS BUILT

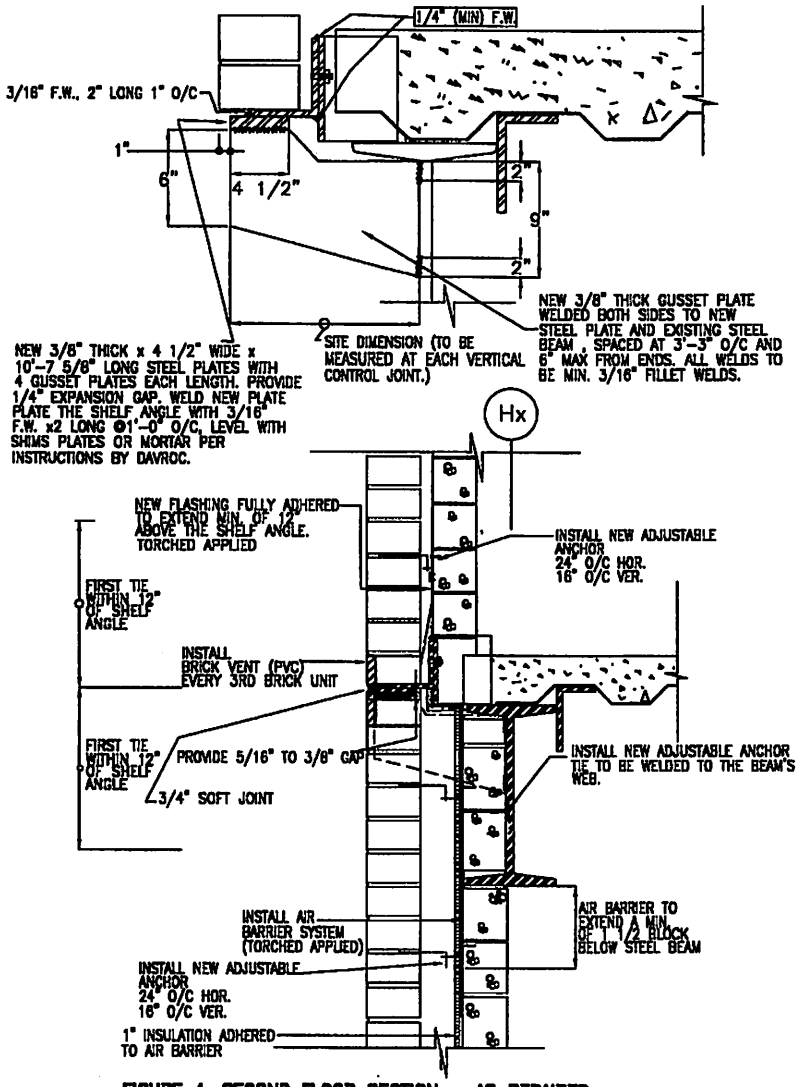


FIGURE 4. SECOND FLOOR SECTION – AS REPAIRED

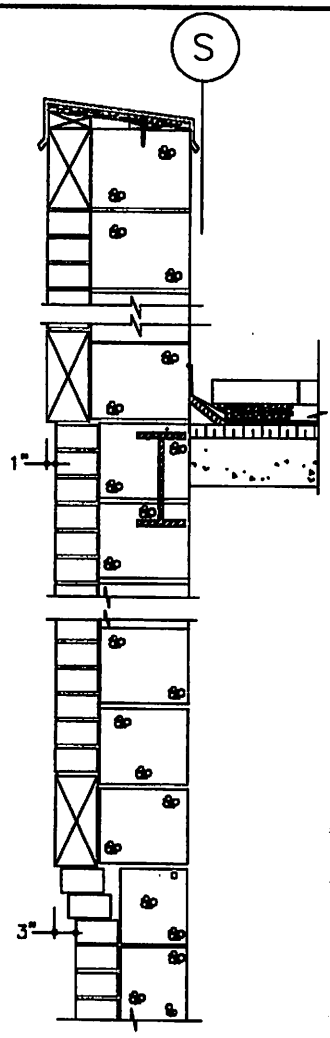


FIGURE 5. SOUTH WALL SECTION – ORIGINAL DESIGN

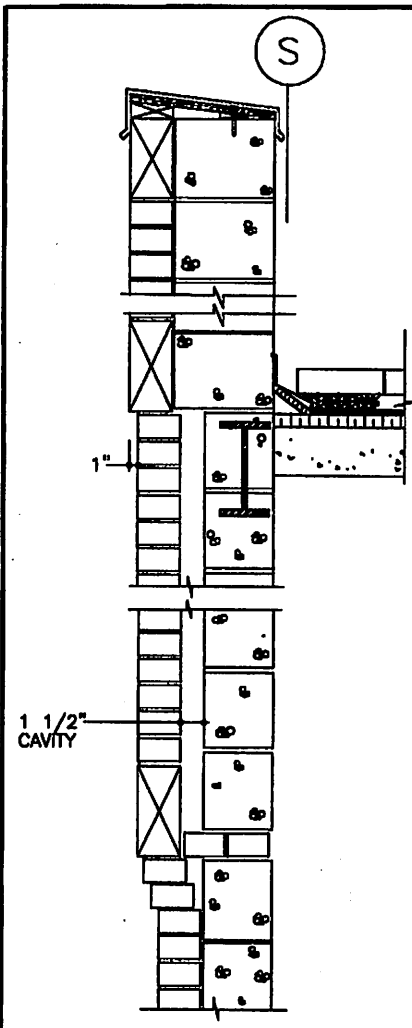


FIGURE 6. SOUTH WALL SECTION – AS BUILT

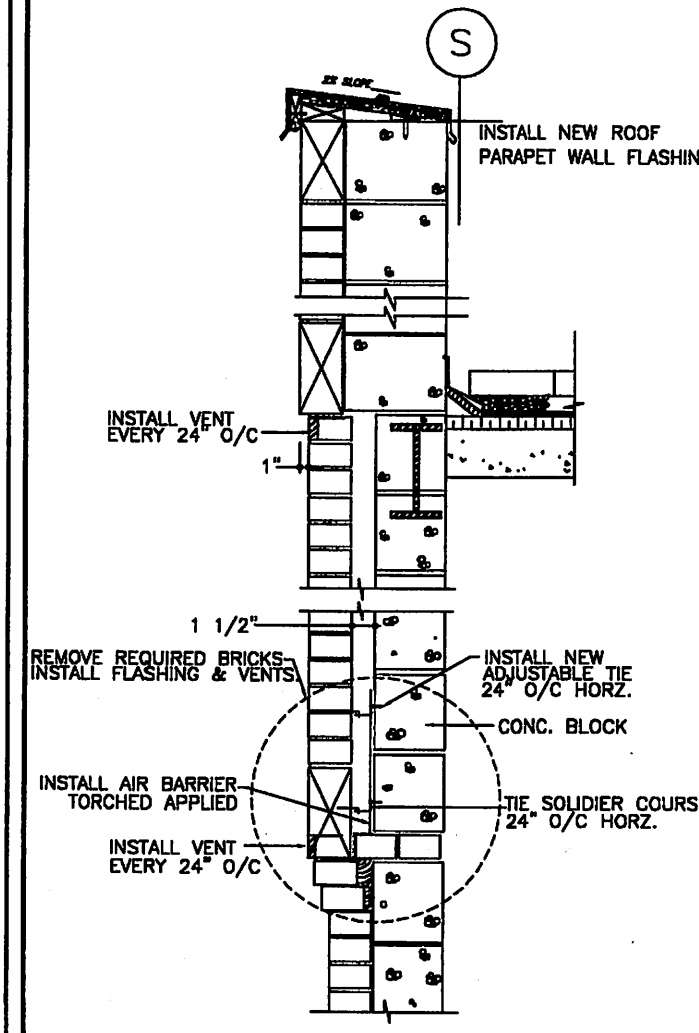
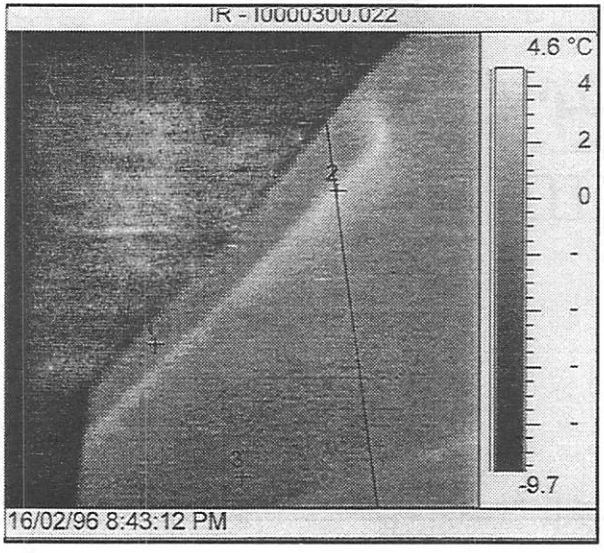


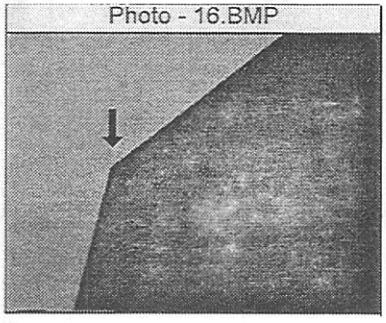
FIGURE 7. SOUTH WALL SECTION – AS REPAIRED

FIGURE 8.

LOCATION:

NORTH WALL THERMOSCAN





Results

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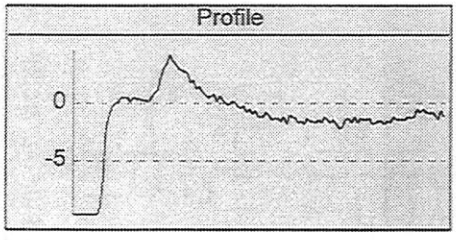
	Temp
SP01	-2.2
SP02	4.0
SP03	-3.0

	Min	Max	Diff	Avg	Med
LI01	<-9.7	4.1	*13.9	*-1.2	-1.1



DESCRIPTION: THERMOGRAPH SHOWS A VERY DISTINCT HEATING OF THE HORIZONTAL SOFT JOINT AT THE STEEL SHELF ANGLE. THESE PATTERNS ARE TYPICAL OF INTERIOR AIR EXFILTRATING INTO THE WALL CAVITY AND WARMING THE LOCAL BRICK.

Figure 9. South Parapet Wall

Temperature vs. Time

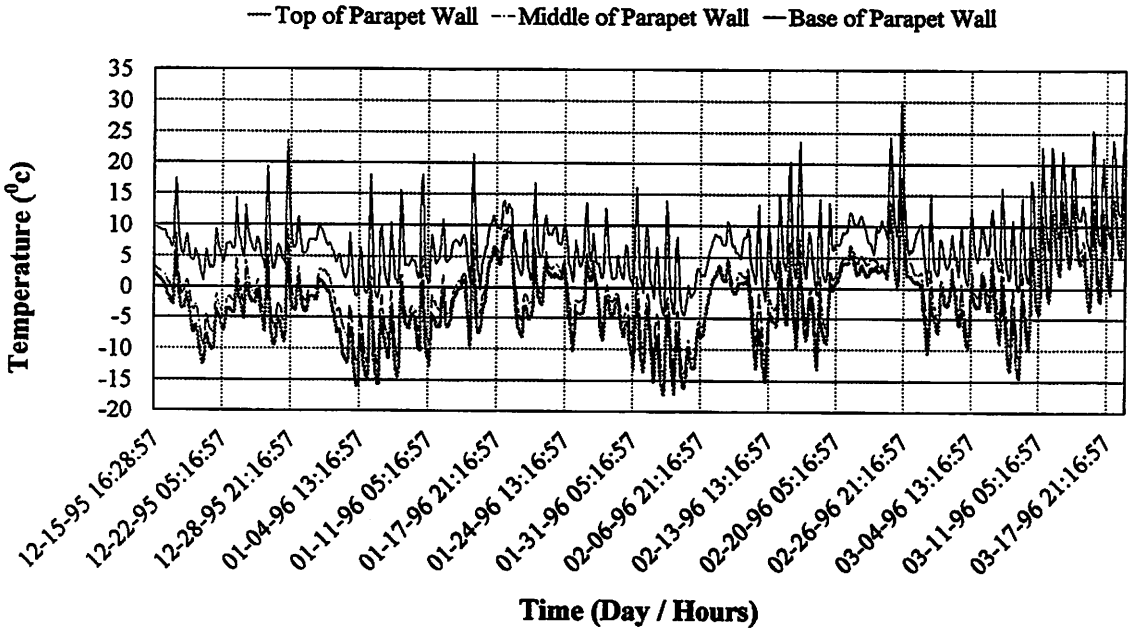


Figure 10. South Parapet Wall

Humidity vs. Time

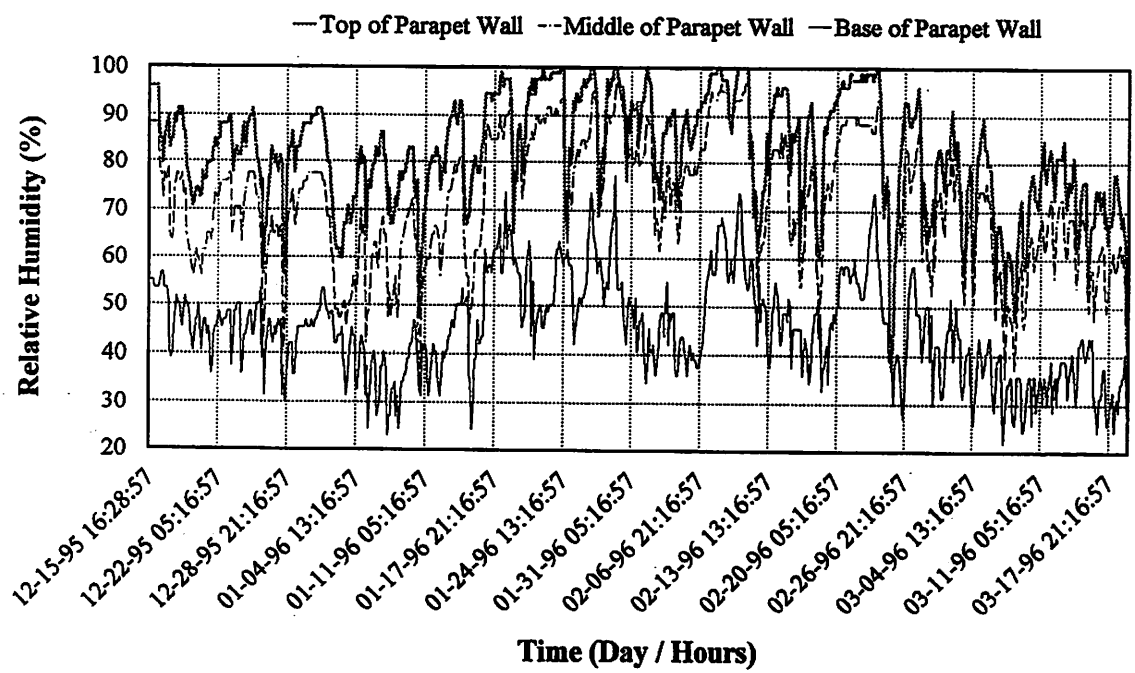


Figure 11. Water Vapour Transmission Tests

Lab Test Program - Block Sealer vs. Brick Sealer

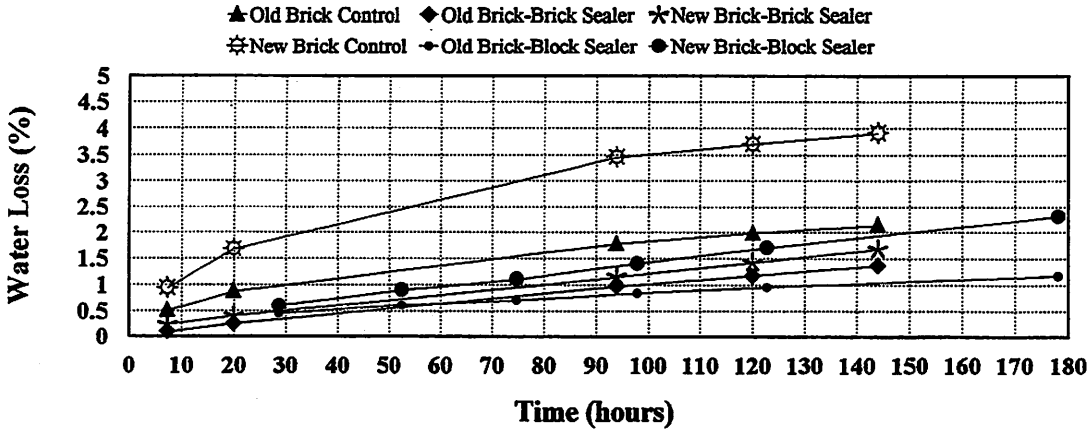


Figure 12. Surface Absorption Tests

Lab Test Program - Block Sealer vs. Brick Sealer

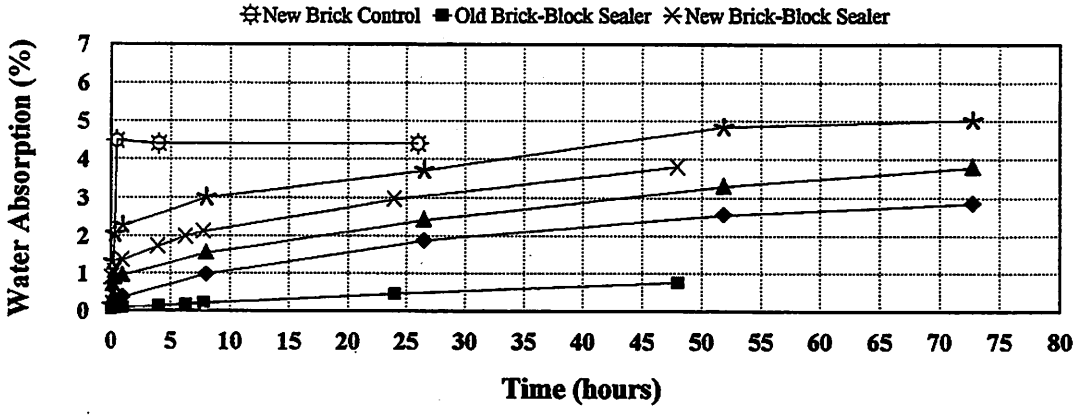


Figure 13. Surface Absorption Tests

Evaluation of Site Sealed Bricks

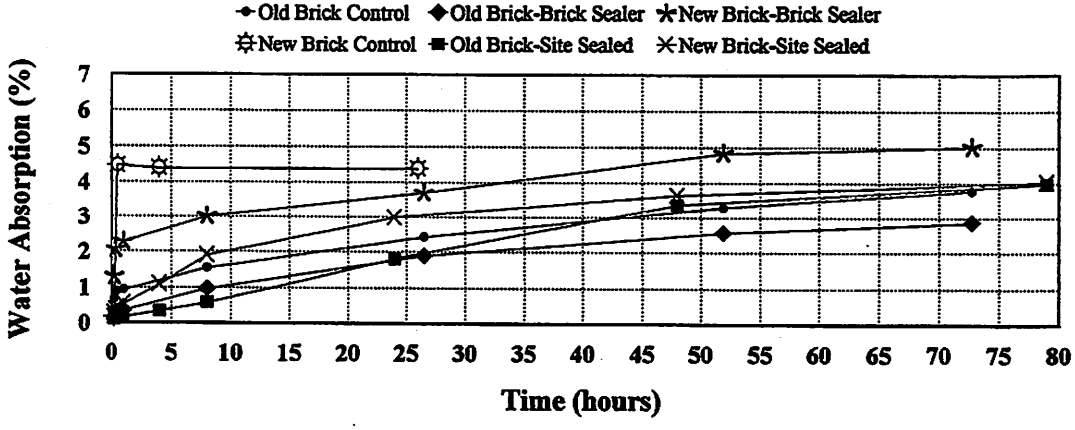


Table 1. Temperature and Humidity Data Loggers Summary

Location	Temperature		Relative Humidity	
	Min. (°c)	Max. (°c)	Min. (%)	Max. (%)
North Parapet - Two Story				
Top of Wall	-19.36	9.95	90.7	100
Middle of Wall	-16.13	11.95	N/A	N/A
Base of Wall	-12.26	12.54	N/A	N/A
South Parapet - Two Story				
Top of Wall	-17.19	16.17	37	100
Middle of Wall	-14.56	18.09	32.4	97
Base of Wall	-4.54	30.19	21.7	77.2
South Parapet - Single Story				
Top of Wall	-16.39	17.44	N/A	N/A
Base of Wall	-10.74	21.15	52.2	100
South Parapet - Single Story				
Mid-Height	-11.75	24.83	N/A	N/A
South Parapet - Single Story				
Outside Air	-17.9	24.07	6.7	97.1
Mall				
Inside Air	19.43	23.32	7.0	34.3

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Study of the Impact of Thermal Bridges In Two Sprayed Polyurethane Wall Assemblies

D. Derome[1], G. Desmarais[2], J. Rao[3], A.K. Athienitis[4], and P. Fazio[5]

Abstract

This paper presents results on the thermal performance of two novel wall assemblies tested in a recently developed environmental chamber. The tests were conducted to investigate the thermal impact of polyurethane sprayed in a 38 mm layer on the exterior of the wood studs in large scale specimens (4m x 7m). While current residential wood stud wall assemblies incorporate panels of semi-rigid insulation on their exterior side to prevent thermal bridging, the tested assemblies use blown in-situ insulation materials, one specimen with high water permeance material and the other with low air permeance material. In the latter case, the insulation is also the air barrier of the assembly as its installation can be done after all puncturing elements of the envelope have been installed, thus inducing complete sealing.

The two wall assemblies used each a different insulation method : the first one used a 127 mm thick layer of low-density water-based polyurethane, and the second one a 38 mm thick layer of medium-density polyurethane plus a 89 mm thick layer of cellulosic fiber. Both specimens have the same wood structure and two floor junctions : one standard lumber wall/floor junction and another one with prefabricated I-joists. The measured thermal performance of the two assemblies, using the guarded hot box test method (ASTM C236), is presented and compared to calculations based on measured thermal resistances of the materials (ASTM C518) and 3-D finite difference calculations. The reduced impact of thermal bridges due to the assembly technique is demonstrated for both specimens by comparing their performance to a base case by finite difference analysis. Collected data included impact of relative humidity, thermographic images at different simulated outdoor temperatures, and air leakage under pressurization using standard ASTM E283 method. The same series of tests is planned to be repeated in 12 months to study the impact of curing and aging.

Keywords : wood stud wall assemblies, thermal bridge, polyurethane insulation, thermal performance.

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Study of the impact of thermal bridges in two sprayed polyurethane wall assemblies

D. Derome, M.Eng., G. Desmarais, B.Arch., J. Rao, Ph.D.,
A.K. Athienitis, Ph.D., and P. Fazio, Ph.D.

Introduction

A typical residential building wall, in recent canadian construction, consists of batt insulation between the wood studs covered, on the cold side, with sheathing and semi-rigid insulation. The vapor barrier, usually a polyethylene sheet, is installed on the hot side. The gypsum board on the inside often acts as the air barrier. In terms of thermal resistance, these assemblies meet the codes, but the overall air leakage can be important, e.g. the mean air change per hour at 50 Pa was 3.3 in a study on Quebec new residences [1]. A proposal to improve the performance of this assembly was devised by an insulation contractor. A research project was undertaken to study this assembly at the Building Envelope Performance Laboratory of the Centre for Building Studies (CBS).

The wall assembly

The wall assembly employs a technique for enhancing the overall performance of residential walls without significant change on construction site practices and with negligible impact on the construction schedule. It employs polyurethane sprayed from the interior of the house into a 38 mm layer comprised of furring and fiberboard on the exterior side of the wood studs, as shown in figure 3. This insulating layer acts as the air barrier in addition to moderating the effects of thermal short-circuits through structural components, that are vertical studs and header joists. The main advantage of sprayed insulation is its ability to use the substrate as formwork and adhere to it. The remaining space between the studs is filled with cellulosic fiber held in place with polyester mesh to prevent setting after the installation and insure a constant density. Cellulose is used for two reasons: it prevents air gaps between the sprayed material and the finishing boards, while increasing the thermal resistance, and it is less expensive than polyurethane. Furthermore, to fill also the space between wood stud framing with polyurethane would require a labor extensive trimming of the solidified material.

This new assembly has been applied in several houses with standard polyurethane. One house was tested for air leakage. The blower door results yielded 0.9 air change per hour (ACH) at 50 Pa differential [2], which is below the requirements of 1.5 ACH for air leakage in the R–2000 home program. The infiltration was found to be mainly through the basement sliding windows and the patio door. As the polyurethane manufacturer involved in this project had a new water-based low-density polyurethane, it was decided to test first the structure completely insulated with flexible insulation. In doing so, it was hoped that the flexibility of the

insulation would allow excess blown insulation to be eased in between the studs. In fact, the insulation protruding edges had to be trimmed manually. Once tested, the water-based insulation was removed, and the structure reinsulated to proceed with the study of the combined insulation strategy.

The properties of the insulating materials are given in Table 1. The standard test method ASTM C518 for steady-state heat flux measurements and thermal transmission properties by means of the heat flow meter apparatus [3] was applied to measure the thermal resistance of the three insulation materials used in the large scale tests. Three specimens of each material were tested. These tests were performed simultaneously with the large scale tests in the environmental chamber for similar curing times of the polyurethane.

Table 1 - Measured (C518) properties of the insulating materials used in this project

	Water-based polyurethane	Polyurethane	Cellulosic fiber
Density [kg/m^3]	7.37	32 @ 35	48
C518 measured thermal resistance for thickness used in large specimen [m^2 °C/W] (accuracy ±2%)	2.68	1.78	1.91

The CBS Environmental Chamber

The large scale tests were performed in the recently developed Environmental Chamber of the Building Envelope Performance Laboratory housed at CBS. This facility was designed to study all major hygrothermal (air, moisture and heat flows) aspects of building envelope performance simultaneously, including its interaction with the indoor environment, under controlled simulated outdoor and indoor conditions. Full technical details are given elsewhere [4]. The environmental chamber consists of two separate chambers representing indoor and outdoor conditions, denoted as hot and cold boxes respectively (see Figure 1). A hollow rectangular frame is sandwiched between the hot and cold boxes, in which building envelope components can be fixed or built up for steady-state or dynamic thermal tests. A metering box is located on the hot box side of the test specimen to measure heat flow for the thermal resistance measurement based on the guarded hot box method (ASTM C236 [5]). Without the metering box, this facility can be used for tests similar to the calibrated hot box method (ASTM C976 [6]). Experiments can be performed on envelope assemblies with maximum dimensions of 7.2 m high by 4.1 m wide by 0.6 m thick. Without a specimen in the frame, the facility is used as one large environmental chamber for the testing of full rooms.

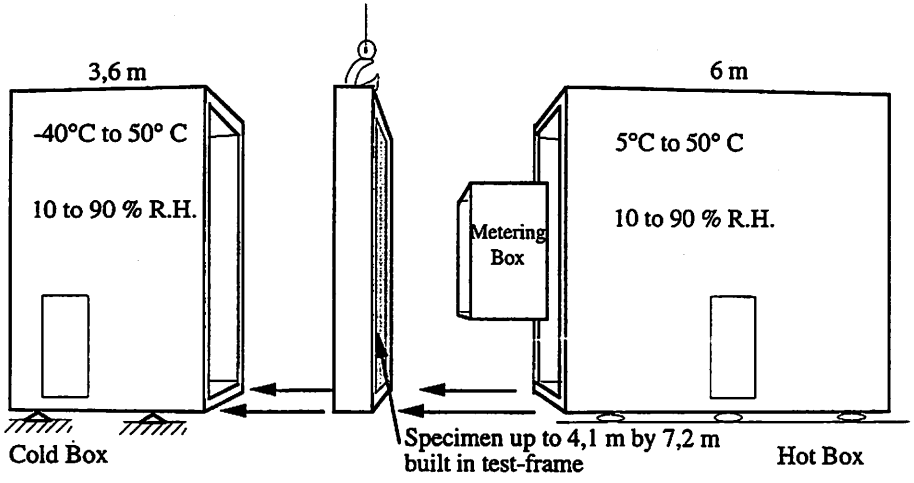


Figure 1. Schematic of the Environmental Chamber

Testing procedure

Specimen construction

The wood structure, as shown in Figure 2, was built by workers directly within the test-frame of the Chamber. The workers applied standard nail fastening methods. The wall was composed of 38 mm x 89 mm wood studs at 400 mm on center, with 38 mm x 38 mm horizontal wood furring on the cold side at 400 mm on center. On the furring, 12 mm asphalt impregnated fiber board sheathing of medium density was nailed. Vertically, the structure had three sections, a lower section with vertical studs of 1,450 mm high, then a header joist with ends of floor joists, made of prefabricated wood I-joist, a middle section of wall 3,600 mm high, a second floor junction with regular 38 mm x 190 mm wood joist, and finally, an upper section of wall 1,450 mm high.

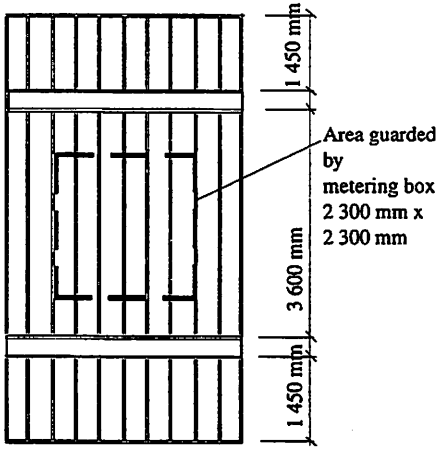
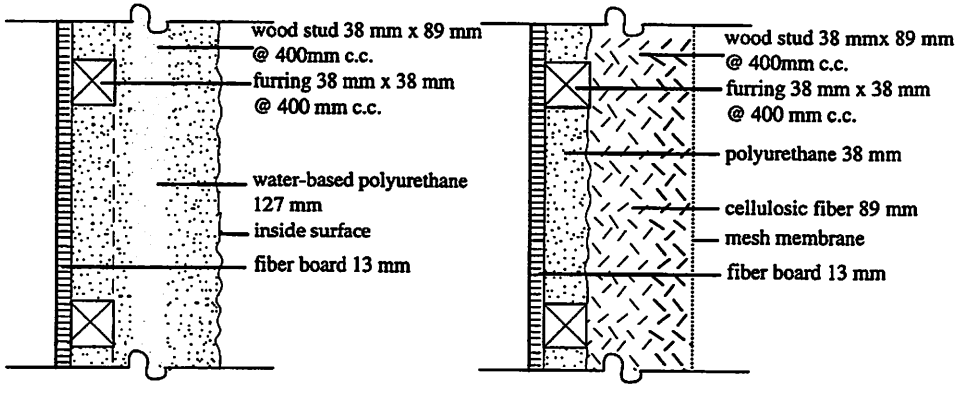


Figure 2. Front view of assembly

The area guarded by the metering box corresponds to the central part of the 3,600 mm middle section. The distance between the edges of the guarded area and the top and bottom floor junctions ensures symmetrical boundary conditions.

The first specimen was insulated only with low density water-based polyurethane sprayed between the furring and the studs. After tests were completed on the first specimen, all low-density polyurethane was removed and replaced with two insulation materials: the space between furring was insulated with sprayed standard polyurethane, and the space between the studs was insulated with blown-in cellulosic fiber held in place by a mesh attached to the stud prior to installation. No vapor barrier was included in order to study the impact of moisture transfer due to different indoor relative humidities on the overall thermal performance.



Specimen 1 Specimen 2

Figure 3. Section details of tested assemblies

Thermal resistance

Measurements of the global thermal resistance were performed using the guarded hot box method (ASTM C236). The temperature differences across the surfaces of the metering box were minimized, insuring no heat transfer across the walls of the metering box. The heat required to maintain constant temperature in the metering box is therefore equal to the heat flow through the specimen. The average thermal resistance for the area of 2.3 m x 2.3 m facing the metering box is determined as the ratio of temperature difference to heat flow.

$$Q = U\,(T_o - T_i) \qquad (1)$$

where : T_i = average temperature on the interior (hot) surface of the specimen [°C], measured with 25 thermocouples;

T_o = average temperature on the exterior (cold) surface of the specimen [°C], measured with 9 thermocouples;

U = measured thermal conductance, [W/m^2.°C];

Q = heat required to maintain the metering box temperature constant minus calibration loss [W].

In this setup, the influence of edge effects, which alters the heat flow direction from one-dimensional into three-dimensional, is minimized.

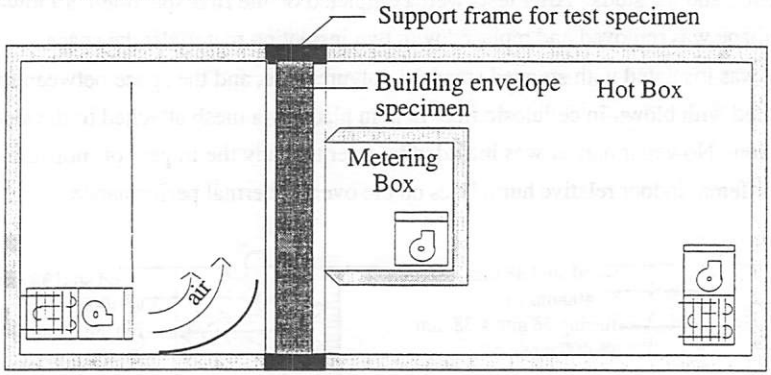


Figure 4. Experimental setup for ASTM C236

Each specimen was instrumented with 108 calibrated thermocouples for the C236 test and three heat flux transducers. The accuracy of temperature measurements was ±0.2°C.

Testing sequence

Five tests were conducted on the first specimen and 12 tests on the second. Temperature differentials and relative humidity were chosen to represent the extremes of the Montreal winter climate (-40°C to -20°C) and the widest range of relative humidity in homes (from 10 % to 70 % R.H.). Tables 2 and 3 list the test conditions for specimens 1 and 2 respectively. All the tests were conducted in the sequence shown in the tables.

Thermographic images

Thermographic images were taken with an infrared camera to verify the uniformity of the insulation and observe the effects of the presence of thermal anomalies.

Results

Thermal performance

The C236 results for different temperature differentials are found in Tables 2 and 3. The vapor barrier was intentionally absent from both wall assemblies in order to correlate indoor relative humidity and temperature differentials for relatively short time period relative to the time constants of moisture migration. In each test, the results were taken when steady state conditions in terms of temperature were observed after 24 hours, as per ASTM C236. As a result, it was not expected to reach steady state in terms of moisture transfer. No tendencies were observed for different relative humidities in the case of specimen 1. As for specimen 2, the measured R-value when the cold side was at -20°C and -30°C decreases with higher relative humidities and stays low once relative humidities were lowered. This tends to indicate a build up of moisture in the

hygroscopic cellulosic insulation. The presence of this moisture does not affect results for the coldest outside temperatures.

Table 2. Thermal resistance results for five C236 tests conducted on specimen 1

test	Temperature in hot box [°C]	Temperature in cold box [°C]	Relative humidity	R-value[m^2.°C/W]
1	20	-20	23 %	2.57
2	22	-30	20 %	2.72
3	24	-20	60%	2.55
4	24	-35	40%	2.74
5	22	-20	70%	2.58

Table 3. Thermal resistance results for 12 C236 tests conducted on specimen 2

test	Temperature in hot box [°C]	Temperature in cold box [°C]	Relative humidity	R-value[m^2.°C/W]
1	24	-20	40%	3.46
2	24	-20	33%	3.39
3	24	-25	36%	3.35
4	24	-40	35%	3.48
5	24	-30	30%	3.40
6	24	-20	60%	3.27
7	24	-30	55%	3.29
8	24	-40	60%	3.48
9	24	-35	55%	3.44
10	24	-20	25%	3.21
11	24	-30	20 %	3.34
12	24	-35	10 %	3.41

Thermography

As seen on figure 9, data show that the surface temperature of the light water-based sprayed polyurethane was not uniform, indicating voids or cold spots within the insulation. In dismantling the first specimen immediately after the last test, ice was found in an intermediate layer of the insulation at the bottom of the panel. Furthermore, several air pockets occurred throughout. This product being new, the professional installer had his first contact with the material, which explains the lack of uniformity in installation. The intermediate layer of ice was located between two sprayed coats in air pockets.

The second specimen thermographic results show a uniform surface temperature of the polyurethane/cellulose system, indicating more consistent performance through out the specimen. Figure 9 shows that the surface temperature fluctuates more on specimen 1 than on specimen 2. This reduced fluctuation indicates a lower impact of thermal bridges in the thermal behavior of the second specimen. This was expected as the R-value of the insulation installed in front of the wood studs is higher in the second case.

Air leakage

It was mentioned above that the performance of the assembly at one site showed low air permeance. On that issue, a laboratory test was performed on the second specimen only, since the water-based polyurethane installed in the first specimen had not been designed with low air permeance. The ASTM E283 Standard test method for the rate of air leakage through exterior windows, curtain walls, and doors under specified pressure differences across the specimens [7] was followed. The accuracy of measurement was ± 5 %. At a differential pressure of 50 Pa across the wall assembly, the measured air leakage was 6.9 CFM (3.24 l/s), which is equivalent to 0.11 l/s·m^2. This transposed on a volume representing a typical bungalow of floor area of 150 m^2 represents 0.25 air change per hour. At 75 Pa of differential pressure, the air leakage for the assembly is 8.5 CFM, equivalent to 0.14 l/s·m^2. The requirement of the National Building Code [8] is 0.02 l/s at 75 Pa pressure differential for air barrier panel or membrane, not accounting for junction detailing.

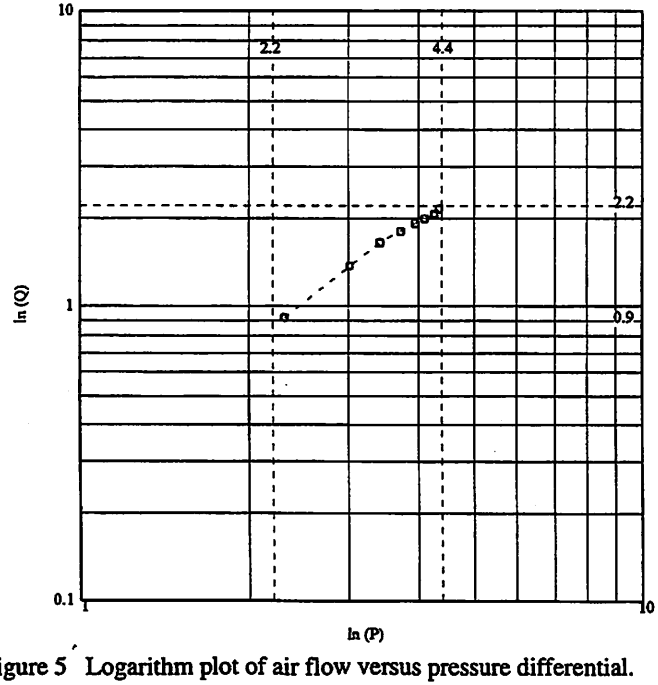


Figure 5 Logarithm plot of air flow versus pressure differential.

Analysis

To allow for comparison between the measured thermal resistances of the insulating materials and the walls, analytical methods were used to derive the overall thermal resistance of the wall using the measured material resistances. A first calculation uses the parallel path and isothermal methods. The actual R-value is generally expected to be between these two extremes.

The second analysis consisted of developing a 3-D finite difference model of the main wall assembly. A 64-node model was constructed using MathCAD as the supporting software. This method is described in [9]. The section studied consisted of one quarter of the total volume from center to center of the vertical studs and center to center of the horizontal furring (the rest being symmetrical). The boundary conditions were the outside and inside air temperatures of the tests.

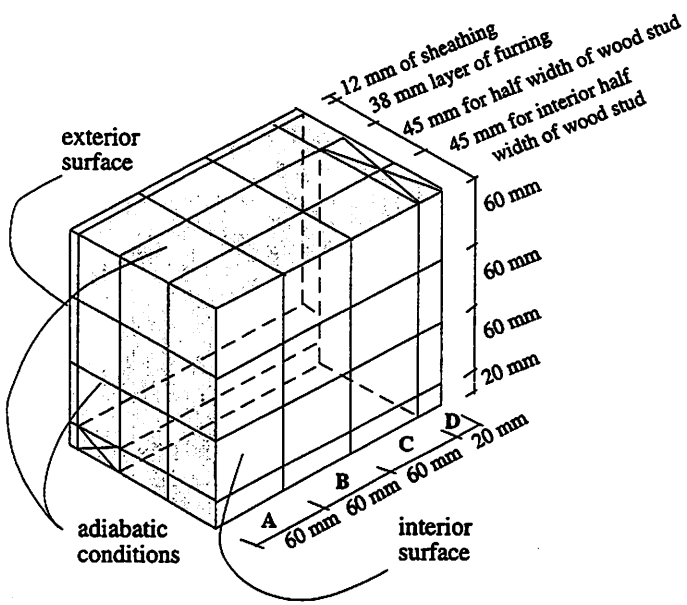


Figure 6. Schematic axonometric view of the 64-node model with its four cross sections showing position of the nodes.

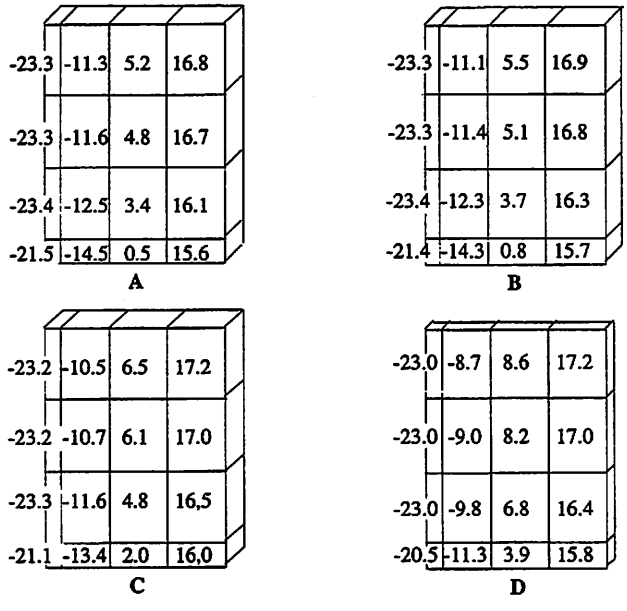


Figure 7. Cross-sections of the 64-node model showing temperature at the center of each control volume. A, B, C, D refer to figure 6.

Figures 8 and 9 show the local impact of the thermal bridges, from the interior surface as seen by the thermographic scans and as modeled. Table 4 summarizes the analytic and experimental data. In both cases, the analytical methods yield overall R-value in good agreement with the experimental results. With a finite difference model, the analysis was pursued in terms of the impact of the thermal bridges. Each specimen was modeled as having 38 mm x 140 mm wood stud, thus without furring, everything else remaining the same. Table 5 lists results for this comparative modeling as well as the framing effect factor which compares global thermal resistance to the thermal resistance of the assembly at the center point between wood members.

The area of the thermographic images shown in figure 9 covers a section of the floor connection with similar surface temperatures as the rest of the assembly. This indicates that, for both specimens, the polyurethane insulation sprayed in between the exterior sheathing and the perimeter joist is uniformly applied.

Specimen 1 - modelled as tested

22.24	22.26	22.30	20.56
22.23	22.25	22.29	20.53
22.19	22.21	22.25	20.43
22.15	22.17	22.20	20.34

Specimen 1 - modelled with 38 mm x 140 mm

22.24	22.24	22.21	20.19
22.24	22.24	22.21	20.19
22.24	22.24	22.21	20.19
22.24	22.24	22.21	20.19

Specimen 2 - modelled as tested

22.67	22.70	22.75	21.45
22.64	22.66	22.71	21.37
22.55	22.57	22.61	21.16
22.45	22.47	22.51	20.95

Specimen 2 - modelled with 38 mm x 140 mm

22.66	22.64	22.55	20.68
22.66	22.64	22.55	20.68
22.66	22.64	22.55	20.68
22.66	22.64	22.55	20.68

Figure 8. 3-D model results in term of the interior surface temperatures.

Table 4. Summary of experimental and analytical data for thermal resistance, [m^2 °C/W].

	Specimen 1	Specimen 2
Experimental results	C236 Test 1 at $\Delta T = 40°C$ 2.57	C236 - Average of tests 1 and 2 at $\Delta T = 44°C$ 3.43
Analytical results*		
parallel path method	2.71	3.59
isothermal plane method	2.56	3.11
average of both methods	2.64	3.35
finite difference	2.67	3.49

* using measured thermal conductance according to ASTM C518, $\Delta T = 25°C$.

Table 5 - Finite difference results for R-value on assemblies with and without furring

	Specimen 1 [m^2 °C/W]	Framing effect 1 - $R_{effective}/R_{center}$	Specimen 2 [m^2 °C/W]	Framing effect 1 - $R_{effective}/R_{center}$
Thermal resistance at center of assembly (R_{center})	2.92	N/A	3.94	N/A
Model results of wall assemblies as tested	2.67	8.6 %	3.49	11.4 %
Model results of assemblies without furring	2.62	10.3 %	3.31	16.0 %

Discussion

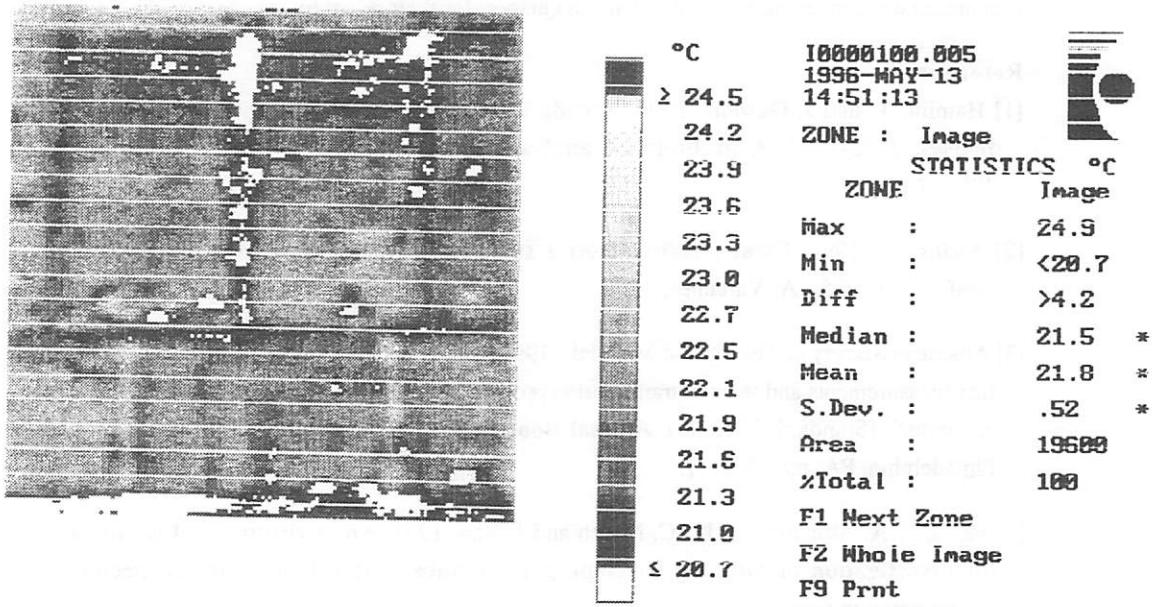
Polyurethane has a high thermal resistance and uses the envelope components as its permanent formwork. Proper application insures no internal gaps as demonstrated by the thermography in specimen 2. The low temperature spots appearing on the thermographic image of the interior surface of specimen 1 were most probably due to both the inexperience of the applicator with the new product and the rapid expansion of the product. The high airtightness of the second assembly confirms the capacity of polyurethane to fully fill the space in between studs. The main innovation of this assembly is spraying from the interior the polyurethane on the exterior side of the wall studs, thus preventing heat losses through the thermal bridge that wider wood studs would be. As demonstrated by the finite difference models results, the framing effect is diminished and the assembly successfully reduces heat losses through thermal bridges. An attempt was made to correlate indoor relative humidity to thermal performance. Short testing time rendered this inconclusive, but some trends were perceived on the hygroscopic insulation material performance that would be worth pursuing.

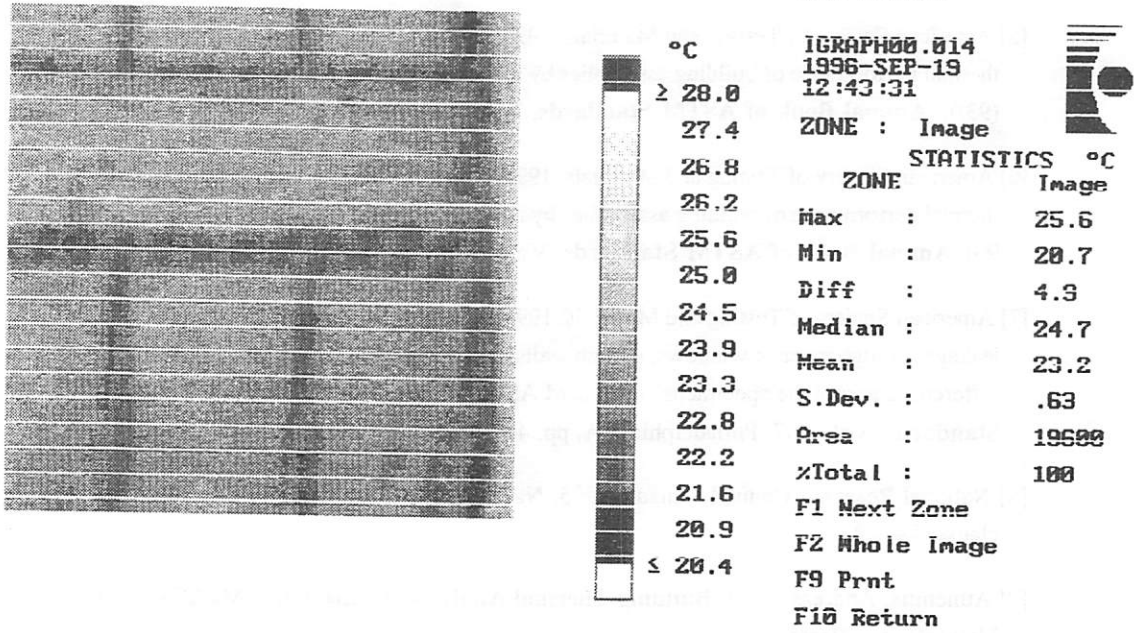
Issues of the durability and stability of the polyurethane have not been addressed in this paper. A second series of tests on specimen no. 2 is planned one year after the first study. Recently, heat flux meter results of the same polyurethane specimens seem to indicate a loss in thermal resistance within the first six months.

Conclusions

Two large-scale wall specimens were tested in an environmental chamber. The standard test ASTM C236 was performed at different temperature differentials and relative humidities. Analysis of the data and comparison with calculations performed with measured resistance values of the insulation materials demonstrated a reduced impact of thermal bridges due to the assembly technique. This appears to be due to the capability of the sprayed material to fully fill voids, which was further demonstrated with an air leakage test on the second specimen.

Figure 9 Thermographic photos of specimens 1 and 2





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Mechanical And Electrical Systems - Most Common Deficiencies and their Impact

Peter Cook[1]

Abstract

Over the past decade, Trow Consulting Engineers Ltd. (Trow) has carried out building audits on many high rise residential buildings in the Greater Metropolitan Toronto Area and surrounding Municipalities. In carrying out those audits, Trow discovered that the shortcomings in the mechanical and electrical systems of the buildings often resulted in a seriously compromised building performance and costly repairs.

This paper will review the deficiencies that were most commonly noted in a large number of these technical audits. The paper will list the symptoms of these problems, their impact on building performance and examples of costs of repair. Where applicable, the paper will also indicate whether these deficiencies are most often construction shortcomings, or lack of maintenance. Codes and legal requirements will also be discussed with an explanation as to which are mandatory and which are not.

This information will assist the property manager and building operator in knowing when these problems are likely and their relative impact on building performance.

Key Words

Mechanical, Electrical, Construction, Deficiency, Maintenance, Insulation, Heat Tracing, Pressure Gauges, Sprinklers, Heat Detectors, Equipment Identification, Dielectric, Backflow Preventer, Fire Wall Penetrations, Carbon Monoxide, Ventilation, Vibration Isolators, Aging

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Mechanical And Electrical Systems - Most Common Deficiencies and their Impact

Introduction

In preparing this paper, the author reviewed over 50 reports prepared on building mechanical and electrical systems as a result of technical audits, due diligence audits and reserve fund studies. These reports were taken at random from several hundred reports prepared by Trow. Many of the deficiencies listed in the reports reviewed occurred only once or twice. While many of these are not unique in the author's experience, they have been omitted here in the interest of brevity and on the understanding that they are less common in high rise residential buildings.

The more commonly observed deficiencies will be discussed here under two categories: Low Cost Housekeeping Items, and High Cost Items Leading to Projects. Each measure will be discussed in terms of symptoms, impact on building performance and cost of repair. A summary of applicable codes, standards and by-laws is also included

Low Cost Housekeeping Items

These common faults are not expensive to repair. Many can be corrected by the building maintenance staff. While some are best done by an experienced contractor, even in these cases, the cost is low and the work can be undertaken without capital expenditure approval.

Damaged or Missing Pipe Insulation and Equipment Insulation

This is an extremely common deficiency observed in residential buildings. It is normally a result of a lack of maintenance. Symptoms would include over heating of boiler rooms, condensation on, and subsequent rusting of chilled water and domestic cold water piping, and poor performance of heating and cooling systems. Most cases observed involved only small sections of pipe or equipment where insulation had been damaged or removed during service. There is no specific code requirement for insulation of cold mechanical piping and equipment, however, the Ontario Building Code[2] does require that pipes exposed to human contact must be insulated so that the exposed surface does not exceed 70°C (158°F) . In any case, very hot surfaces, such as diesel generator exhaust pipes and boilers should be insulated to prevent accidental burns for which the building owners or operators could be held liable.

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[2] Ontario Building Code 1990, CL 6.2.9.2.(6)

The cost of repairing insulation is minimal. However, where possible, an experienced contractor should be retained to insulate to the same standards as the existing installation including a continuous vapour barrier on the outside of insulation on all cold pipe and equipment. If this contractor were retained to replace or apply insulation throughout a building or group of buildings economies of scale could be achieved.

Missing Insulation and Heat Tracing in Unheated Areas

While related to the above issue, this fault occurred often enough to warrant separate comment. This deficiency can be maintenance related, but is most often a construction deficiency. The most obvious symptom is freezing and breaking of water systems in the unheated area. Occasionally, the freezing or partial freezing will result in only a blockage of the flow. In these cases it is wise to take steps to heat and thaw the services in question as quickly as possible in order to mitigate damage. In some cases observed, insulation was provided, but heat tracing had not been provided, even though it was specified. The Ontario Fire Code requires that fire protection systems be protected from freezing. While other codes are less specific as they apply to other mechanical systems, the most important issue here is the cost of repairs and the damage to property.

It is important to note that experience is not necessarily a predictor of the future here. Most of the deficiencies observed were in unheated parking garages. Depending on the operation of the ventilation systems and the severity of the weather, freezing conditions which have not occurred for a number of years could occur suddenly without warning. The question is not "how often is this condition going to occur?", but rather "will this condition ever occur?".

The cost of correcting this fault varies greatly from a minor housekeeping issue as described above (freeze protection insulation need not be vapour sealed and it is, therefore, not as important that it be carried out by an experienced contractor), to a small project. The latter condition includes those situations where the contractor has neglected even to run a power supply to the location of the pipe. In some instances, pipe insulation must first be removed in order to apply the heat tracing, then reapplied after the heat tracing is installed.

Pressure and Temperature Gauges

This issue has little direct impact on the operation of the building. Pressure gauges are required under the Ontario Fire Code at various locations and where these are missing they must be installed. Pressure and temperature gauges on other mechanical systems will allow the building operators and maintenance personnel to note the operating condition of pumps, boilers, chiller and coolers at a glance, thus leading to better overall performance and averting costly failures. Most of the incidences noted in these studies appeared to be the result of deterioration and lack of maintenance.

The cost of replacing gauges is nominal. Most gauges can be purchased for an average of approximately $100, and most operating personnel are capable of installing these gauges.

Loose Receptacles and Damaged Cover Plates

In many older residential buildings, several examples were noted where receptacles in suites were loose or the cover plates were damaged. This is normally due to age of the building, lack of maintenance and in some cases, abuse by the residents. Most of these deficiencies would almost certainly have been listed by a fire or electrical inspector if one had occasion to inspect the building.

The cost to replace cover plates is nominal and can be carried out by the building operators or the residents. Loose or damaged receptacles can be more difficult to correct and will require the services of a licensed electrician.

In a condominium building, this item would not be part of the common element and would often not be a concern of the building manager. However, due to the potential fire hazard here, this item in particular should be taken seriously and a pro-active role should be taken by the building operators.

Electrical Equipment Shielded from Sprinkler Spray

The standards regarding fire protection sprinklers require that all rooms in buildings or areas of a building being sprinklered, have adequate sprinkler coverage. This includes electrical equipment rooms. The Ontario Hydro Electrical Safety Code states that electrical equipment not designed for wet environments must be protected from such an environment. The usual compromise is to provide a metal shield to deflect the sprinkler spray away from electrical equipment. Any room containing electrical panels and switchgear which is sprinklered and does not have obvious metal

shields above the equipment likely falls into this category. The condition is most often the result of a construction oversight. If not corrected, this condition could result in a major electrical equipment failure or even a major fire if the sprinkler system were to discharge as a result either an accidental malfunction or a small fire.

The cost of providing adequate shielding is modest, however, a licensed electrician should be retained to carry out his work and the local electrical inspector should be asked to review the finished work.

It is not acceptable to plug the sprinkler openings or otherwise tamper with the sprinkler system in the electrical room. Sprinklers are required in electrical rooms as they are in any other room of a sprinklered building in order to stop a fire in its first stage.

Electrical Panel and Equipment Identification

This is most often a construction oversight and should have been enforced under the Ontario Hydro Electrical Safety Code. While this lack of identification has no direct effect on the operation of the building, it can affect continuous comfort of the tenants and operating cost by increasing the time to solve simple equipment malfunction problems.

This work can usually be carried out by operating or maintenance staff and while it is time consuming, it can normally be spread out over time.

Dust in Electrical Enclosures

This condition is a normal maintenance problem and is very common. Over time the dust can cause arcing of contacts and premature equipment failures.

The cost of cleaning these enclosures is not large, however, the work requires removing the front of the enclosures and should only be done by a licensed electrician.

Loose Connections in Electrical Panels

This is also a normal maintenance problem which is very common in older buildings. If not corrected, loose connections can result in arcing and hot spots, open circuits or loose conductors which fall out of location and short other circuits.

Once again, while the cost of this work is low, it should only be undertaken by a licensed electrician since it requires removal of the front of the electrical enclosure.

Dielectric Connections

Connections between dissimilar metals such as steel and copper piping must be insulated by the installation of a dielectric coupling. This will eliminate current flowing between the two metals which would otherwise allow galvanic action to occur and pitting of one of the metals. If not corrected this condition will result in premature failure and leaking of the piping system.

The cost to correct this is minimal. Dielectric couplings in the sizes normally encountered in residential buildings, typically cost less than $20, and while the piping system must be drained, the work required is normally not extensive.

If a brass valve or fitting is used between the pipes of dissimilar metal, a dielectric coupling may not be required because brass, while a conductor, has a high resistance to the type of current flow associated with galvanic action. Consult a professional engineer or a metallurgist if in doubt.

Backflow Preventers Missing

A backflow preventer consists of two check valves in series with a drainage port in-between them. This device is designed to prevent water from flowing in the reverse direction under all conditions of negative and positive pressure in the piping system. The Ontario Building Code requires that Backflow preventers be provided to prevent the transfer of water from an unsafe system such as certain fire protection system or a sewage system into a potable water system. While the Ontario Building Code is not generally enforceable after a building is occupied, various by-laws and health board rulings generally look to the Ontario Building Code as a standard to be followed.

Fortunately, the lack of these devices does not necessarily result in the spread of disease, foul odour or bad tasting drinking water. The health risks which include the ingesting of harmful bacteria are serious, nonetheless, and Backflow preventers should be provided where required as soon as noticed.

The cost of a Backflow preventer depends on the size and the type required for the specific application. A four inch diameter reduced pressure principle Backflow preventer would cost approximately $800.00 at wholesale price and would cost several times that to install. It is advisable to seek the advice of a professional engineer before proceeding with the installation of a Backflow preventer.

Improper Seal around Pipes, Ducts and Conductors Which Penetrate Fire Walls

While this item does not affect the performance of the building systems in a noticeable way, it is a violation of the Ontario Fire Code and must be corrected. This is usually a construction deficiency, although it occasionally results from maintenance repair work which has not been completed properly.

The cost of providing the correct fire rated seal is nominal and can usually be done by building maintenance staff. It is wise to consult an architect or a professional engineer for a specification of the correct materials and procedure to be used in each location. If in doubt as to which walls need to be fire rated, an architect or an engineer can also be consulted to make that determination.

High Cost Items Leading to Projects

These items can cost more to correct and the work is best done by an outside contractor with input from a consulting engineer. Due to the cost, higher levels of approval within the owner's organization are often required.

Inadequate Ventilation Systems in Parking Garages

In some, but not all cases, fumes associated with engine exhaust are pronounced in the parking garage under certain conditions. If allowed to go without being corrected, this condition can become dangerous to the lives or the health of people using the garage. In some instances, fumes from the garage will make their way into other parts of the building. The Ontario Building Code clearly sets out the volumetric flow of exhaust air which is required for parking garages. The Code also states that where fans are provided they must either run continuously or they must be controlled by a carbon monoxide sensing system which turns the fans on and opens intake air dampers to maintain the carbon monoxide concentration levels below 100 parts per million (ppm). While the Ontario Building Code is not enforced on existing buildings, the Occupational Health and Safety Act is. The Minister of Labour has the authority to inspect the buildings and to close the garage if the carbon monoxide levels are above 100 ppm.

Costs to correct these deficiencies vary depending on the problem some representative figures would include the following:

Cost of a carbon monoxide detection system with four remote points installed and wired to start two fans	$10,000

Cost to replace two existing fans which are defective, where wiring, openings and louvers can be reused in a 50 car garage.	$50,000

Where no system exists the cost will depend on type of control, size of the parking garage, proximity of electrical power, and building modifications required to provide the openings to draw air into the garage and to exhaust air out of it

In general, while carbon monoxide monitoring systems are costly, they pay for themselves with fan energy saved in one or two years.

Missing Heat Detectors, Smoke Detectors and Sprinkler Heads

While these deficiencies will not affect the day to day performance of the building, they could be very serious in the event that a fire should break out in the room where the device is missing.

In the case of sprinklers, the fact that the coverage is not complete can affect the fire insurance premiums paid. Some of these deficiencies observed were construction oversights, but many were obviously the result of building modifications being carried out without due consideration of the fire protection system. In the latter case, the danger is generally increased because the area where no coverage is provided, is often a small area not frequented by anyone and where fires can start and grow without being detected.

The costs of correcting these faults vary greatly depending on the capacity of the existing systems, zoning and the number of devices missing. In most cases, a consulting engineer should be consulted, or, in the case of a missing sprinkler, a sprinkler contractor, should be contacted for advice and assistance. Generally speaking, the original sprinkler contractor is in the best position to advise on the installation of additional sprinkler heads.

Vibration Isolators Missing

Major rotating mechanical equipment, such as compressors, chillers, fans, and diesel engines all vibrate. If that vibration is not damped and isolated, it will be transmitted to the building structure, disturbing the occupants. These problems are common causes of complaints.

Missing vibration isolators are usually a design or construction oversight. Sometimes isolators, particularly spring isolators, are not adjusted properly, fail or are damaged. In these instances, the repair or replacement is not as costly.

Costs to install vibration isolators, after installation and connection of the equipment is complete, vary depending on the size of the machine, the weight of the machine, the amplitude of the vibration, and most importantly the number of services and attachments which must be relocated. The installation of vibration isolators will require that the vibrating equipment be elevated anywhere from half an inch to eight or nine inches. This will mean that electrical feeders, duct connections and piping connections must be revised. In most cases, if these service connections were not flexible before, they will have to be made flexible with the addition of flexible connections, hoses, metal pipe bellows and flexible wiring. Where the equipment is located on a roof, flashing details will have to be modified. In some cases, the structural elements in the building may have to be modified or stiffened to better support the load.

Aging Equipment

This category covers many problems in building systems, some of which can be corrected temporarily, but many of which will eventually require the replacement of systems or components in their entirety. This is not to say that equipment must be replaced once it has reached the final anniversary of the "expected life" of that type of equipment. As long as a piece of equipment is functioning satisfactorily, there is no need to replace it. But there comes a time in the life of any piece of mechanical or electrical equipment when it must be replaced.

Common symptoms include the following:

Damaged fan casings which contribute to fan noise and bearing misalignment.

Hot spots in electrical panels which cannot be corrected.

Leaking fan coil units.

Leaking cooling towers.

Leaking boilers which can no longer be repaired.

Chillers which are loosing charge or leaking water.

Roof top equipment which is allowing rain into the building.

Equipment for which parts are no longer available.

In the case of larger equipment such as chillers, cooling towers boilers and large fans, the cost of rebuilding the equipment should be investigated. In these cases, a consulting engineer should be contacted to study the feasibility of repair or replacement and to estimate the cost with input from suppliers and contractors of refurbishment and replacement.

In some cases, the life of the building itself needs to be considered as well. It is important that this evaluation be carried out by independent parties who stand to gain nothing on the basis of one outcome over another.

Codes, Standards and Laws

In discussing building deficiencies frequent reference is made to Codes and Standards. It is important to note that not all standards are mandatory. Some are simply good practice guidelines while others, such as the Ontario Building Code; are mandatory under some circumstances, but not all.

A summary of Codes and Standards commonly referred to in building audits is listed below together with an explanation of under what condition they are in force.

Code of Standard	Discussion
Ontario Building Code (A regulation under the Building Code Act administered by the Ministry of Housing)	Compliance is mandatory for new construction or where any portion of the building is undergoing a substantial modification which affects the life safety aspects of the building. An exception to this is that some other Codes, such as the Ontario Fire Code, which are mandatory occasionally make reference to requirements of the Ontario Building Code.
Ontario Fire Code (A regulation under the Fire Marshal's Act administrated by the Ontario Fire Marshall's Office. Requirements of this Act may also be mandated by local by-laws made under the authority of the Municipal Act.	Compliance is mandatory at all times. The local Fire Chief has authority to interpret and enforce the requirements of this code as well as local by-laws respecting fire safety.
Occupational Health and Safety Act and regulations (administered by the Minster of Labour)	These requirements affect workers in buildings. Many of these requirements are not specific. In these instances, compliance with the specific requirements of the Ontario Building Code for the same issue will usually ensure compliance with the requirement of the Minister of Labour.

Code of Standard	Discussion
Operating Engineer's Act (Administrated by the Boiler and Pressure Vessels Branch of the Ministry of Consumer and Commercial Relations	Mandatory for some large plants which fall into the categories described in the Operating Engineer's Act.
Ontario Regulation 189/94 respecting "REFRIGERANTS" (A regulation under the Environmental Protection Act, administered by the Ministry of Environment	Mandatory. The implications are not clear in the Regulation, but the intention is that if owners do not exercise "due diligence" with respect to containment of refrigerant leaks, the law will deal more forcefully with them.
Ontario Hydro Electrical Safety Code. (Based on the Canadian Electrical Code, administered by Ontario Hydro and the local Utilities.)	Mandatory. The local Ontario Hydro or utility inspector has the authority to interpret and enforce the Code, by not allowing the system to be connected to a source of power.
Gas Utilization Code (A regulation under the Energy Act Administered by the Fuel Safety Branch of the Ontario Ministry of Consumer and Commercial Relations. Also referred to as CAN/GGA - B149.1 M96)	Mandatory. The local gas supply company has the authority to interpret and enforce the Code by not allowing gas to be supplied to the equipment.
American Society of Heating Refrigeration and Air Conditioning Engineers National Fire Protection Association Canadian Standards Association American Congress of Governmental Industrial Hygienists	These and other similar standards have no force in law by themselves. They may, however, be referenced in a Code or Regulation such as the Ontario Fire Code, or the Ontario Building Code.

This discussion is not meant to be an exhaustive review of the legislation in place, but rather to illustrate that the building owner does not have to comply with all codes and standards. While some owners may wish to incorporate improvements for reasons of service to building users or protection of assets, the best advice with respect to Codes is to ask if a code or standard must be complied with, and why.

Conclusion

This list of most common deficiencies will give the building owner and operator the beginnings of a check list for reviewing building mechanical and electrical systems. However, it is also important to note that this study of Trow's building inspections revealed many deficiencies which occurred on only one or two of the 200 buildings examined. Clearly, while the above list is helpful, it does not cover all the deficiencies. When there is a need to know the condition of your building's systems, the best solution is to have your building's mechanical and electrical systems reviewed by a qualified professional engineer.

7th Conference on Building Science and Technology

COMMON LEAKAGE PROBLEMS IN RESIDENTIAL HIGH RISE BUILDING WALL AND WINDOW SYSTEMS

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INTRODUCTION

Building technology is constantly evolving. New materials and assemblies are continually being developed to address the desires of designers, builders and building owners for building envelopes that are aesthetically pleasing, cost-effective to construct, and durable and economical to maintain. Satisfying these desires is not always easy and often requires trade-offs. The end result, in terms of durability of the building envelope, can be less than desirable from the building owner's perspective, particularly if disruptive and costly remedial work is required to provide an acceptable level of immediate and long-term performance.

The definition of acceptable durability of exterior wall and window systems is a focus of debate in the construction industry. Durability should be defined as a combination of a stated initial performance level and the period of time over which the performance level is expected to be maintained. While Codes and standards are slowly evolving to help define minimum levels of performance, the durability of the performance is too often below the reasonable expectations or

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needs of the building user.

In this paper we discuss several construction details which we have frequently found to be causing water leakage through exterior wall and window systems of highrise residential buildings in the greater Toronto area. Typically, water leakage could have been prevented if certain precautions were taken during construction. These are identified in the text and will be illustrated during the presentation.

Modern Residential Highrise Buildings

Designers and builders of residential highrise buildings built over about the last 10 years have had the benefit of many improvements in building practice that have been found necessary to construct building wall and window systems which perform well over time. However, there continues to be an absence of prescriptive Code requirements or other incentives to motivate providing a level of durability which is acceptable to building owners. This is compounded in situations where the future building owner is not present at the design and/or construction stages, or where the owner does not have the technical ability to define the levels of performance and durability which are acceptable. This absence of Owner input is common in the construction of residential highrise buildings, particularly in the condominium industry.

Builder's warranties, individual component warranties, and home warranty programs have been established to try and protect the interests of future building owners who are not represented during the design and construction stages. Unfortunately, the protection offered by these warranties and programs is usually very limited. They do not provide assurance of acceptable or durable performance. They can have the adverse effect of setting an expectation that minimum mandated performance levels only need to be achieved within the short time period covered by the warranties.

Durability of Resistance to Leakage

It is probably safe to say that water leakage is the most aggravating problem experienced by Owners of residential highrise buildings. Unfortunately, general repair programs to address widespread leakage problems are common within 5 to 10 years after construction. Owing to the

difficulties gaining access to the exterior walls and windows to complete the repairs, the costs of these programs can be significant.

The need to conduct "maintenance" is often used as an explanation as to why such programs are necessary. In some instances, categorizing necessary repairs as "maintenance" may be reasonable. Some degree of imperfection or error in workmanship or materials will always exist and it is reasonable to expect it will be necessary to make local repairs to address areas of isolated premature failure. However, many of the water leakage problems we encounter are a direct result of problems being incorporated into the building envelope at the time of construction. These problems persist despite the mechanisms of rain water penetration having been established and theories on control having been developed and widely published. The causes of many of these leakage problems appear time and again in numerous buildings. Several of these will be reviewed in this paper, in the hope that such problems will become less common in the future.

LEAKAGE PROBLEMS

Masonry Clad Walls

Masonry walls for modern high-rise buildings are generally designed in accordance with the rain screen principle, incorporating an exterior layer of masonry (often clay brick), an intermediate drainage layer or air space. This layered approach is an effective method of reducing the likelihood of rain water penetration to the interior of the building.

Leakage to the interior of buildings as a result of problems with the through-wall flashing at the bottom of the drainage space are frequently encountered. The flashing is required to act as a waterproofing membrane at the base of the wall panel, and as part of a system (together with the air space, weep holes, and drip flashings) to collect and direct water that penetrates the masonry to the exterior. This concealed waterproofing is typically applied by masons. Defects that are incorporated at the time of construction typically do not cause leakage over the short term. However, normal weathering of the masonry and sealants, and exposure to increasingly more severe storms eventually results in sufficient quantities of water penetrating the masonry and entering the cavity to test the effectiveness of the waterproofing.

While defects with the flashing are common, it is fortunate that only some locations of defects lead to leakage problems. Unintentional slope of the flashing away from defects and resistance of the exterior masonry to water ingress often help to avoid extensive problems even where general defects exist.

Typical problems encountered with flashings include:

- *Ends of flashing not turned up.* Architectural details typically show the installation of the flashing with a two dimensional section showing how water is directed out of the wall. However, water that is collected by the flashing can also travel laterally, towards the ends of the cavity. An upturn of the end of the flashing or "end dam" is necessary to prevent water spilling into this joint. Because adjacent materials such as windows are often not present when the masonry and flashings are being installed, proper upturn of the end is frequently omitted due to a lack of a suitable substrate to support the upturn. The mason can be convinced to leave additional material projecting beyond the end of the masonry panel to be turned up in the future, but ownership for completing this task can then become lost due to a lack of coordination between trades. For example, at window openings, the installer may ignore the additional flashing material or cut it away if it interferes with his work.

- *Joints not properly sealed.* The materials typically selected to act as the through-wall flashing are often single ply sheet goods such as vinyl. Joints are introduced at corners and at laps between sections of the material. While the skill, care and attention necessary to splice weld these types of products can be found among a select portion of the roofing industry, this is not in the skill-set of the masonry industry. If an attempt at sealing joints is made, it is frequently made with a convenient sealant that may not stand up to the requirements of waterproofing.

- *Water penetrating under loose-laid flashing materials.* This can be a particular problem where the flashing does not extend beyond the face of the masonry, and caulking applied to seal the horizontal joints between masonry panels directs water back towards the flashing. Problems also arise at balconies where brick is applied directly to the slab without a curb, and above windows where the joint between the supporting steel angle

and flashing membrane is exposed and unsealed.

- *Flashing material that is not tough enough.* Thin, weak sheet materials which are often used often cannot resist damage during subsequent construction activities, including laying of the masonry.

Many of these problems can be reduced by using a self-adhering modified bitumen waterproofing membrane as the flashing material. This material is easier to apply, is self-sealing at joints, can be moulded and adhered to itself to form end-dams without back-up. It is tough enough to resist construction activities and can be self sealing if punctured.

A drawback is this material is its susceptibility to degradation by UV radiation which prevents it from being extended beyond the outside face of the exterior masonry to form a drip flashing. However, this can be overcome by providing a preformed, prefinished sheet steel drip edge to which the modified bitumen flashing is adhered within the wall.

Precast Concrete Walls

It is common for precast concrete panel clad walls to be designed as face sealed or barrier type wall systems. In practice, precast concrete walls designed in this manner work well, mostly because cracking of the concrete is limited so that there is good resistance to water penetration and because joints between panels are relatively few and well defined so that they can be properly sealed with good quality sealants. Leakage problems are usually associated with failure of sealants.

Sealants may either be applied as a single bead at the exterior face of the panel (face sealed approach) or in two layers, one at each face of the panels (rain screen approach). Both can be equally successful, but the two layer rain screen approach has the benefit of a second line of defence against leakage when the exterior sealant fails, which it eventually will. It is for this reason that it two stage joints sealant strategies have become popular.

Architectural details for rain screen joints typically show both sealant beads as if they are

installed from the exterior of the building. Drainage openings or tubes are provided in vertical joints and the inner bead is brought forward through the joint to direct water to the opening or tubes. In theory, this method of sealing joints should prevent leakage to the interior but in practice it often does not because:

- *Inaccuracies in construction.* Inaccuracies in construction of the building structure and manufacture of the panels may reduce the width of the joints, making insertion of the inner bead of sealant and backer rod difficult or impossible from the exterior. Tooling to achieve proper sealant profile and good bond to the sides of the joint is also difficult.

- *Discontinuity of the inner sealant bead.* The inner bead of sealant is often discontinuous across structural elements (columns, shear walls and floor slabs) if installed from the interior of the building.

- *Improper termination of horizontal joints.* Inner and outer sealant beads must be brought together to close off a joint at openings of face-sealed elements such as windows and doors.

- *Ineffective drainage.* Drain tubes may be plugged by sealant, and isolated horizontal joints may not be drained at all if spanning between face-sealed openings.

Prevention of these problems requires that:

- The inner bead of sealant must be applied from the outside of the wall to permit continuous application across structural elements.

- Joint widths should be increased to allow for conflicting tolerances in construction between structure and panels, between individual panels, to allow sufficient width for access to the back of the joint for insertion of backer rod, and for tooling of the inner bead of sealant. Due to construction errors, some joints may still end up being too tight. Precast panels should therefore be designed with sufficient concrete cover at edges to permit grinding or saw-cutting as necessary to increase joint widths prior to application of sealants. Caulking contractors must be charged with making these alterations.

- Inner and outer sealant beads be joined together at junctions with face-sealed components to prevent water within the joints from spilling into the interface joint and being trapped within the wall by the face seal.

- Drain tubes, if used, must be kept open by placing the tube into the joints while the outer bead of sealant is being applied, instead of being pushed through wet sealant.

Cast-in-place Concrete Cladding

Cast-in-place concrete is often used as part of an exterior wall system in high-rise residential buildings. These can be short knee-walls cast on top of the floor slabs, surmounted by windows or full height shear walls which are exposed. These walls provide a face sealed or barrier type of wall construction.

Leakage problems with these types of walls are usually related to cracks which form in following construction due to:

- *Irreversible Structural movements.* Drying shrinkage of the concrete, creep deflection of the floor slabs between structural supports, and deflection of cantilevered floor slabs.

- *Cyclic movements.* Daily and seasonal changes in dimension of the concrete will occur due to temperature and solar gain.

- *Differential movements.* Movements between knee walls and full floor-height shear walls, and between walls and slabs.

Leakage can also occur through construction joints.

To control the formation of cracks, designers may specify inclusion of vertical control joints in the walls. These joints are typically sealed with caulking to prevent water penetration should cracks form in the joints as intended. This often proves ineffective because:

- *Improper location of joints.* Control joints are not specified at high stress locations, such as at ends of bay windows, at supporting structural elements and at mid-span of structural bays.

- *Missing joints.* Frequently, not all of the specified control joints are provided.

- *Control joints improperly constructed.* Control joints may not be properly constructed to encourage cracking. Horizontal reinforcing steel may not be reduced at the joint, or stress created by continuing even a limited amount of steel across the joint may be sufficient to promote cracking.

- *Ineffective sealing of control joints.* Sealants in control joints are often not properly applied to prevent three-sided adhesion which, in the event of cracking, may cause sealant failure.

If cracking is to be reduced to an acceptable level, a significant increase in the number of joints is necessary. Joints should be provided in the exterior concrete walls at the following locations:

- All corners.

- Between walls supported on slabs between shear walls and walls supported on cantilevered slabs.

- Mid span between intersecting shear walls.

- At wall/shear wall junctions.

- Between knee walls and full-height walls.

A flexible sealant must be provided at the exterior face of the joints to prevent leakage through cracks which form later. The sealant must be installed with proper depth to width ratio to promote flexibility. Coating the walls with an elastomeric finish may also improve water leakage resistance, but typically would only be able to resist splitting at fine cracks.

Operable Windows

Modern window systems are available that incorporate rain screen principles and improved energy efficient performance features. However, windows encountered in high rise residential buildings typically consist of less expensive, face sealed systems. These typically consist of thermally broken aluminum frames, fixed sealed insulating glass units sealed to the framing with glazing tape and horizontal sliding sash paired in a rain screen arrangement.

This system can provide effective resistance to water leakage under most circumstances. Laboratory testing in accordance the national standard CA A440-M90 is required to ensure adequate performance of fixed and operable sections under anticipated design conditions. These windows can often achieve acceptable water leakage performance levels. However, in service it is not uncommon for water leakage through the horizontal sliding sash to occur on a frequent basis.

Acceptable levels of performance achieved during testing of selected window units is often not representative of the average window installed at the building. In our experience, alterations made in the laboratory are not incorporated in typical production windows. Minor deviations in workmanship affect the fit of sliding sash and can adversely affect the efficacy of weatherstripping seals. These factors and slight wear of weatherstripping can result in the level of leakage resistance being unacceptable soon after construction.

Drainage openings may also become blocked due to accumulation of dirt, insects or debris in the sill track. Although this can adversely affect the water leakage resistance of almost any window, some designs are much more susceptible than others. A reasonable amount of this type of interference with drainage should be tolerated by the design. Retrofitting windows to include increased drainage and/or ventilation openings is frequently required to avoid repeated damage from leakage.

Window System Joints

Where window frame sections are linked together, simple lap joints or interlocking male/female joints are often provided. These joints are often sealed with an internal bead of sealant immediately before the sections are brought together.

These type of joints and the way in which they are sealed violate the fundamental requirements of accepted joint sealant design. The sealant is only compressed within the joint, it is not tooled and typically does not comply with the necessary width to depth profile. With movements, these concealed joints stand little chance of providing reliable resistance to water leakage.

However, the tight nature of these joints often limits the amount of water penetration that occurs. Where the windows consist of punched windows, slight amounts of water ingress that occur may stay within the walls. This type of "concealed" leakage may dry out but over the long term may cause problems with corrosion of steel studs or fasteners. Where vertically continuous window systems are provided, water ingress that occurs tends to accumulate as water flows down through the building, increasing the probability that the leakage becomes visible.

To correct these joints, an external surface bead of sealant needs to be applied. This must be detailed to accommodate the movements which occur. Unfortunately, this often requires use of a "band-aid" type of detail which is difficult to apply and can be unsightly. However, moving away from the concealed internal seal allows visual review which is a necessary part of maintenance and repair when leakage problems develop. There is an opportunity for a sealant manufacturer to develop a self-adhering sealant "tape" that could be applied to these types of joints.

Window Perimeter Joints

Other joints between windows with adjacent cladding systems are typically face sealed, irrespective of whether the wall system is a rain screen or barrier type. This can be a successful, durable approach. However, failures do occur because:

- *Insufficient bond area.* Window frames often lack a proper return at the outside perimeter to provide sufficient bond area for the perimeter sealant.

- *Insufficient joint width.* Width of joints between window perimeters and surround cladding can be insufficient to allow for insertion of a flexible sealant or to apply a sealant bead of sufficient width and shape which has capacity to resist differential movements between cladding and window. Reductions in joint width often occur because windows are typically mass produced based on a limited number of site measurements which does not allow for variations in window opening dimensions due to inaccuracies in construction of surrounding wall cladding systems and of the building structure.

- *Improper sealant profile.* As a result of insufficient bond area and perimeter joints being too narrow, perimeter sealants are often applied as fillet beads. These beads are often not applied sufficiently wide to have proper bond area to the frame and adjacent cladding. In many instances, they are also not provided with bond breaker tape or backer rod to achieve a proper profile and allow for movement.

CONCLUSION

Several common problems with the construction of exterior wall and window systems for highrise residential buildings have been presented. All can be avoided during construction to provide increased durability with respect to resistance to water leakage. Changes to building codes, standards, and designer specifications are necessary to reduce the extent of building envelope leakage problems incorporated into new construction.